Best Practices in Dam and Levee Safety Risk Analysis

IV-4. Internal Erosion

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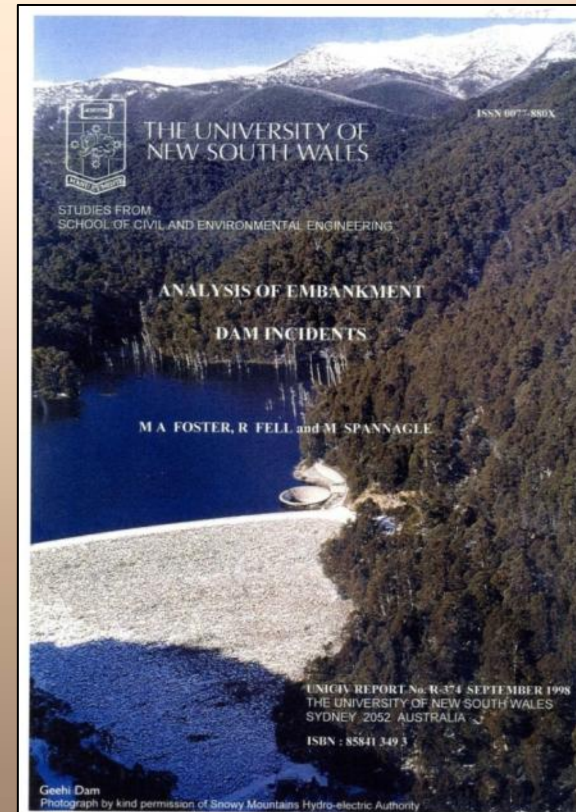
Internal Erosion in Embankments and Foundations

- One of the leading causes of failure of embankment dams has been internal erosion.
- Because internal erosion can occur due to "normal" operations, it may pose higher risks to a dam than remote loading conditions like floods and earthquakes.
- Similarly, internal erosion is a major concern for levees.

UNSW Statistics on Embankment Dam Failures

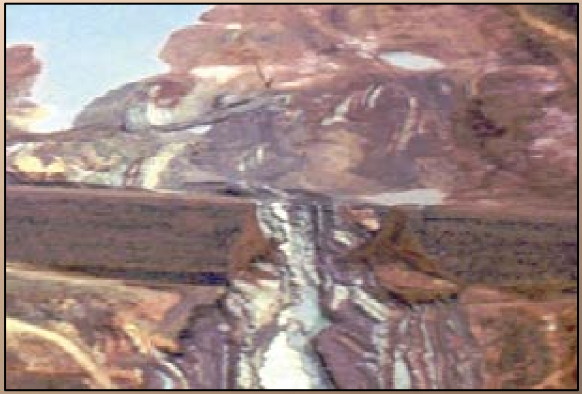
- UNSW (Foster et al., 1998, 2000) looked at historical frequencies of failures and accidents in embankments of large dams constructed from 1800 to 1986:
  - 47% of failures due to internal erosion
  - 48% of failures due to flood overtopping or appurtenant structure failures
  - 4% of failures due to static slope stability
  - 2% of failures due to seismic failures, including liquefaction



Notable Failures

- For Reclamation, Teton was the most significant.
- Additional examples include Quail Creek Dike, Baldwin Hills Dam, and numerous others.
  - Many of which have been or will be a subject of a monthly Case History webinar.

Teton Dam



Quail Creek Dike

Baldwin Hills Dam

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Teton Dam

- Reclamation dam in Idaho
- Failed catastrophically on June 5, 1976 during first-filling of the reservoir
- 300-foot high dam released a nearly full 300,000 ac-ft reservoir
- 11 fatalities and damages estimated to range from $400 million to $1 billion

Teton Dam

- Failure attributed to internal erosion of embankment into foundation
- Zoned earthfill dam with low plasticity loessial core, founded on jointed volcanic rhyolite
- Dam breached within roughly 5 hours of muddy seepage being observed at downstream groin

Quail Creek Dike

- Washington County (Utah) Water Conservancy District
- Failed in 1989 after 4 to 5 years of operation
- 80-foot high dike; reservoir release of 25,000 ac-ft
- No fatalities but $12 million in damages
- Due to internal erosion of embankment into foundation

Wabash River Levee Unit No. 8

- USACE-constructed levee in Daviess County, Indiana
  - Rated “unacceptable” in 2003
  - No longer active in the Corps’ Rehabilitation and Inspection Program
  - Failed in 2011 during only a 1 in 7-year flood, which was only the 13th highest.
- Due to backward erosion piping in the foundation
  - 4- to 6-ft toe ditch excavated by a farmer just prior to flood

Notable Incidents

- Reclamation: Fontenelle and A.V. Watkins are two of the most severe
- USACE: East Branch and Wister are two important cases
- Other examples include Caldwell Canal, Davis Creek, Willow Creek
  - Many of which will be discussed in this training and/or are a subject of a case history webinar.

Fontenelle Dam

East Branch Dam

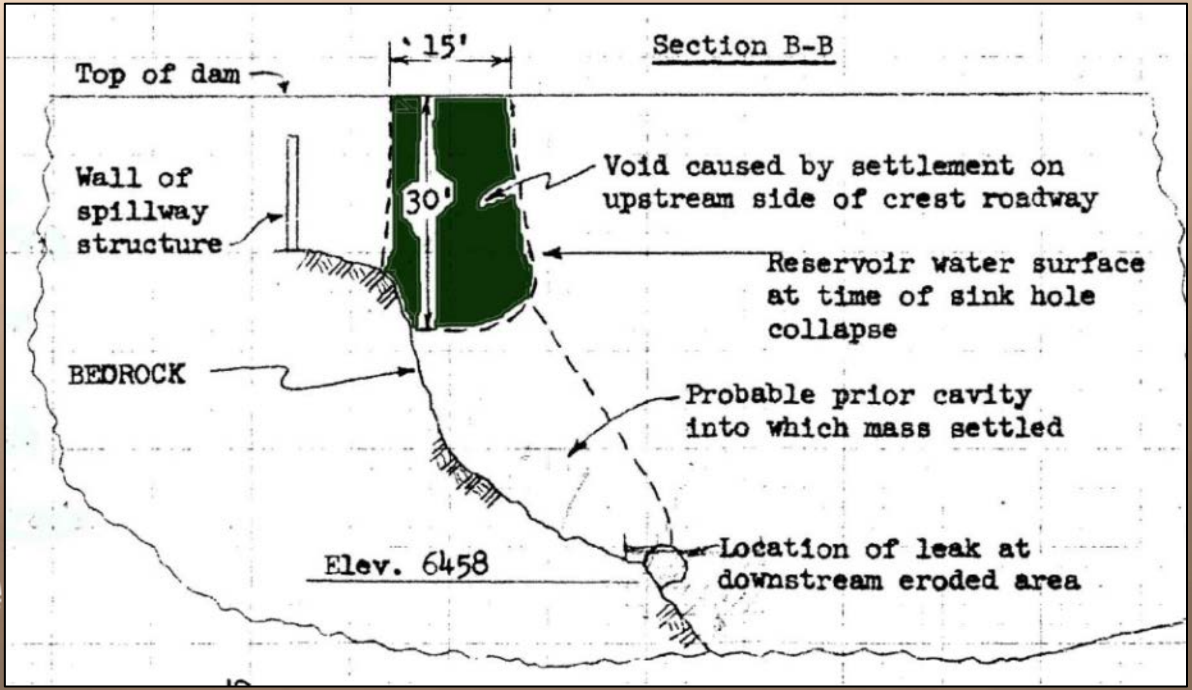
Wister Dam

Fontenelle Dam

- Reclamation dam in Wyoming
- Experienced a severe incident in September 1965 during first-filling of the reservoir
- Large sinkhole formed near spillway, and more than 10,000 cubic yards of material was eroded away by seepage flows

Fontenelle Dam

- Incident attributed to internal erosion of embankment into foundation
- Zoned earthfill dam with low plasticity core, founded on jointed (stress relief) bedrock
- Dam may well have failed if not for ability to lower pool level.

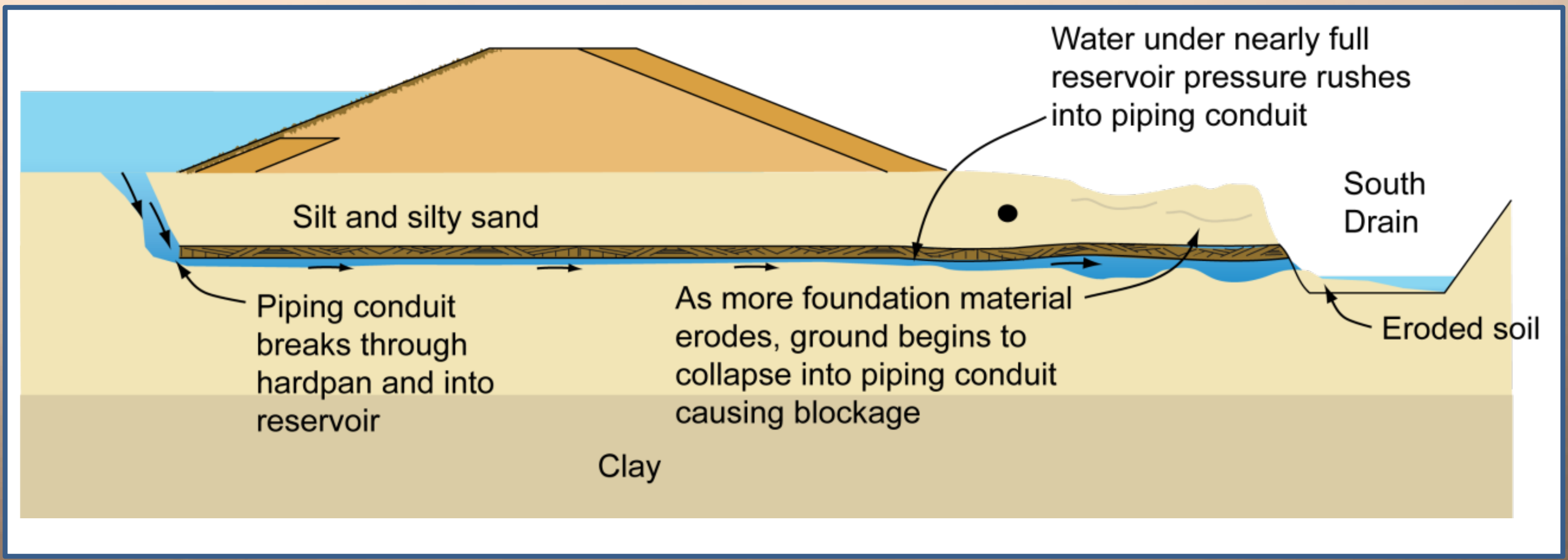


A.V. Watkins Dam

- Reclamation dam in Utah
- Nearly failed in November 2006, after over 40 years of successful operation
- Particle transport, muddy seepage, and sinkholes located downstream

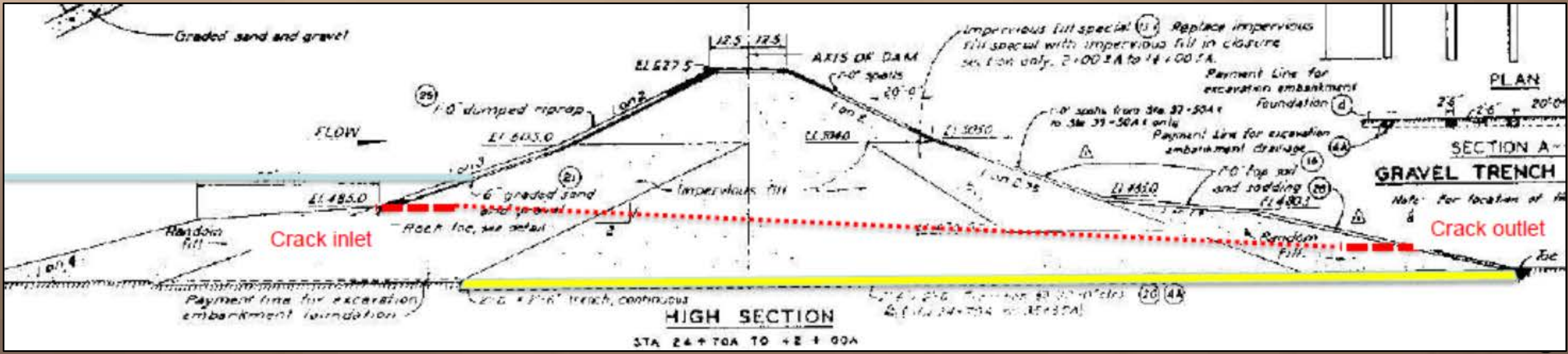
A.V. Watkins Dam

- Internal erosion mechanism was backward erosion piping in foundation sands beneath a caliche roof.
- Embankment would have likely failed without intervention efforts both at the downstream toe and the upstream face.



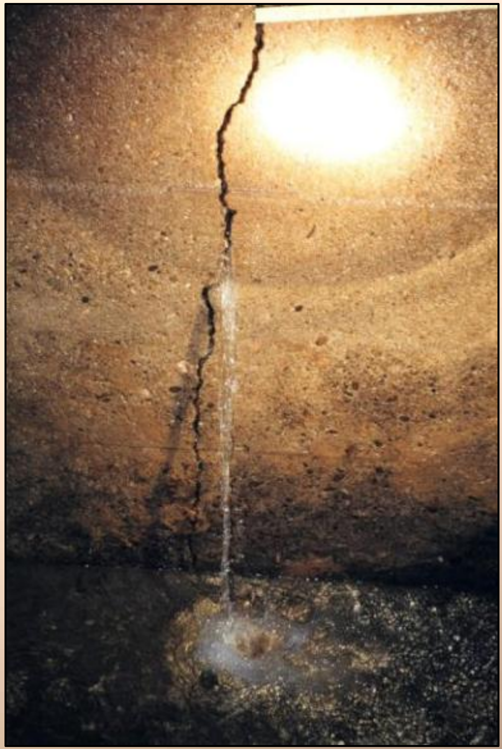
Wister Dam

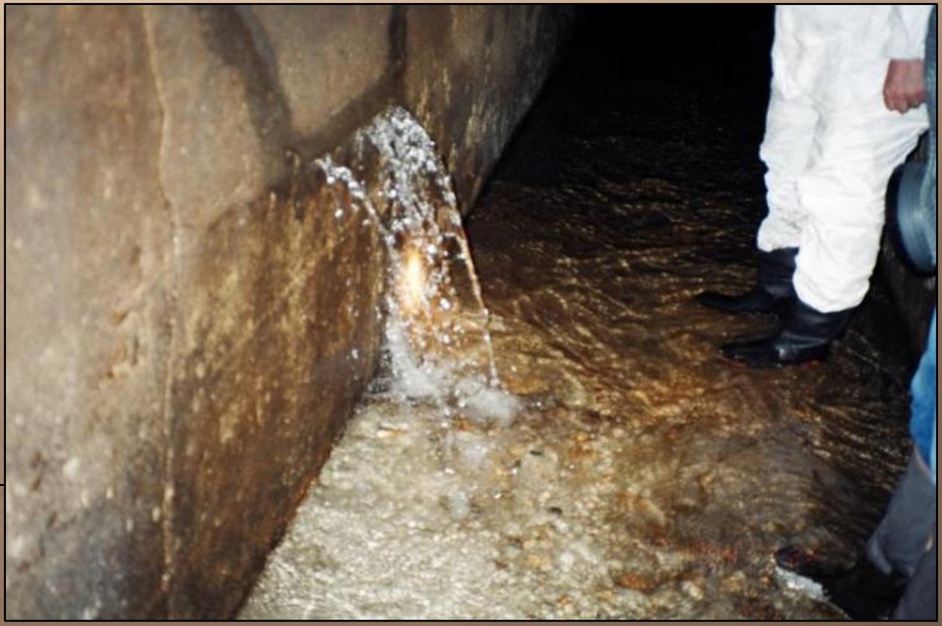
- USACE dam in Oklahoma
- Experienced serious internal erosion in 1949 during initial filling
- Muddy seepage emanated from downstream face (under a gradient of only 0.02)
- Believe to be a result of cracking due to differential settlement
- Case of internal erosion through the embankment



Deer Flat Dam
Caldwell Canal O/W

- Reclamation dam in Idaho
- Required emergency actions in 2006 after 94 years of operation
- Seepage transported embankment materials into conduit through cracks
- Significant voids found under much of conduit length
- Case of internal erosion into/along conduit





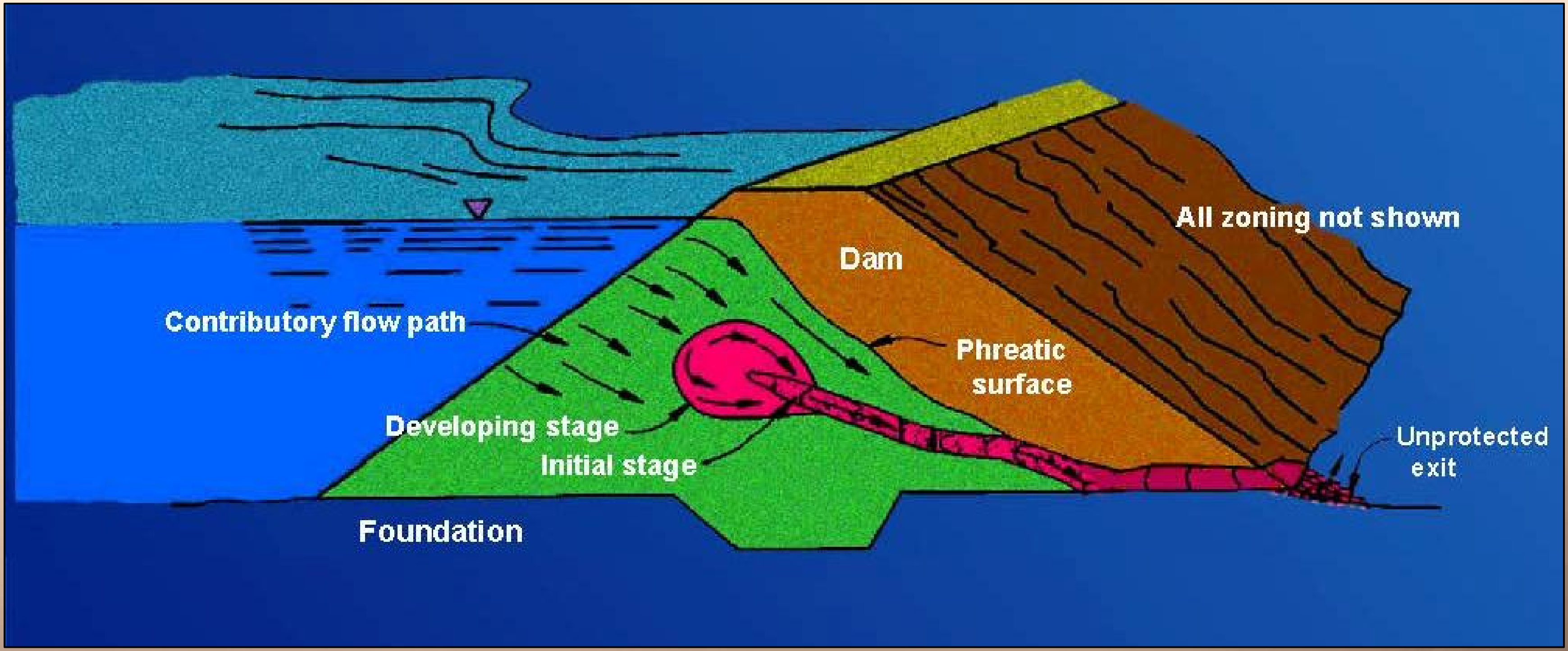
Ensley Levee

- USACE levee in Memphis, Tennessee
- 300-ft long seepage berm added in 1990 consisting of bottom/fly ash
- During spring 2011 "epic" Mississippi River flooding, ±30 sand cones observed (2.5 feet tall and 10 feet in diameter)
- Several pipe collapses identified in early 2012

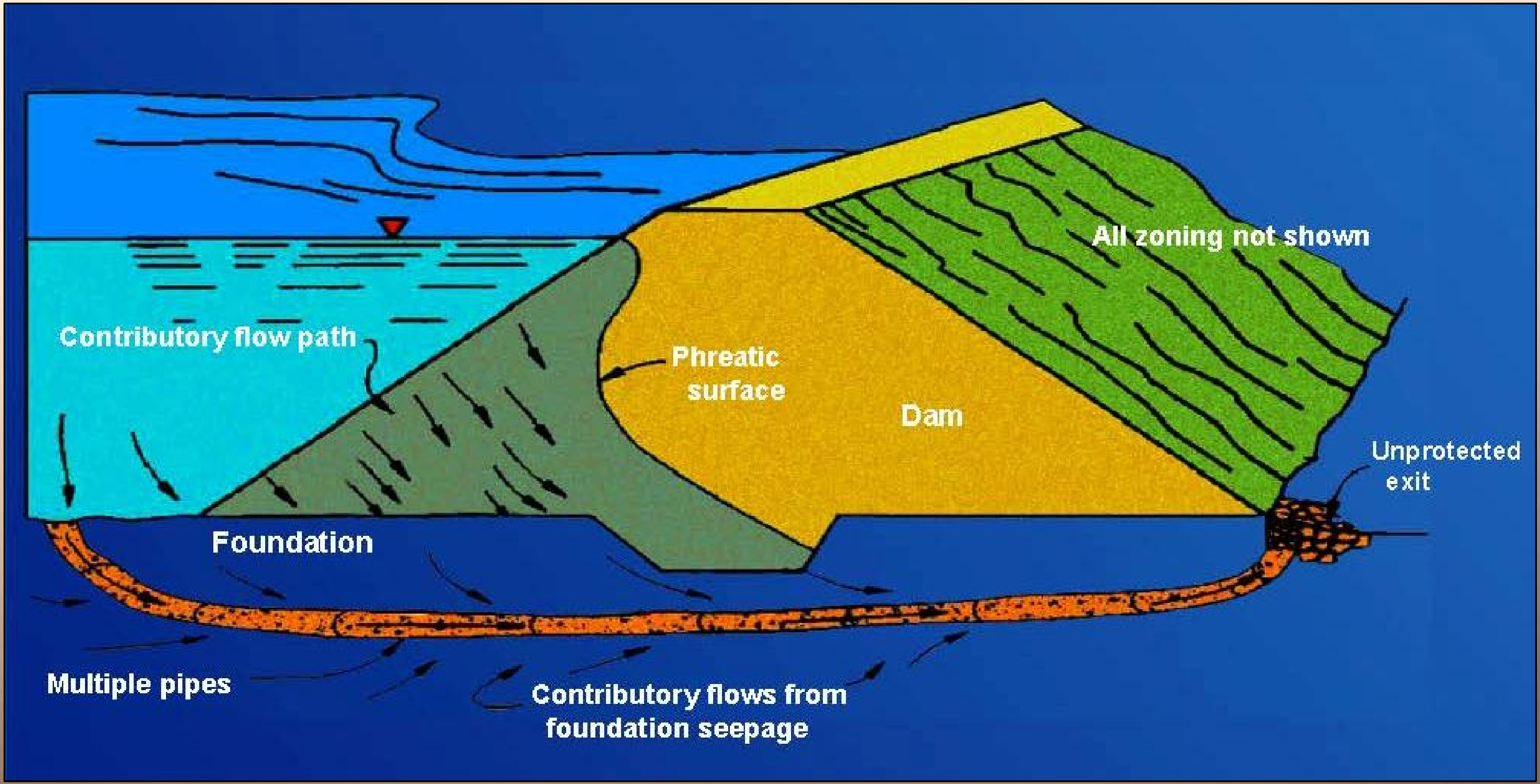
General Categories of Internal Erosion

- Internal erosion potential failure modes can be categorized into general categories related to the physical location of the internal erosion pathway:
  - Internal erosion through the embankment
  - Internal erosion through the foundation
  - Internal erosion of the embankment into the foundation, including along the embankment/foundation contact
  - Internal erosion into/along embedded structures such as conduits or spillway walls
  - Internal erosion into drains
- These are *not* potential failure mode descriptions.

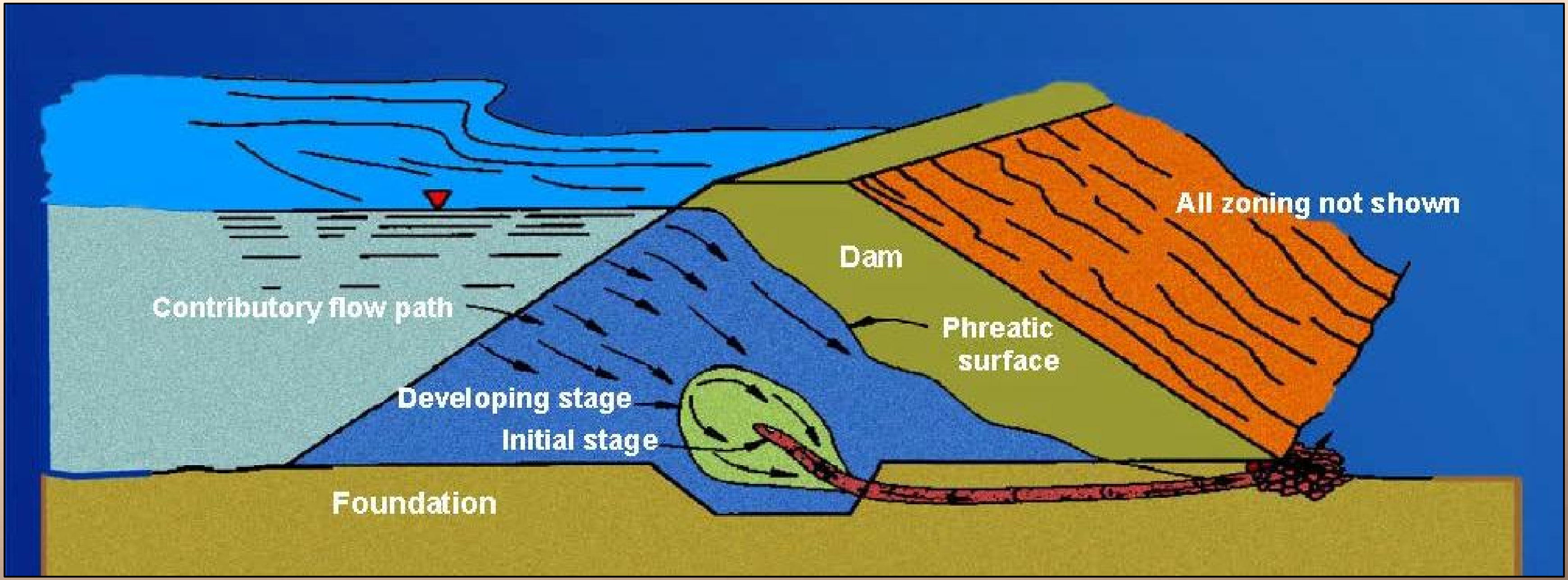
Internal Erosion through Embankment



Internal Erosion through Foundation



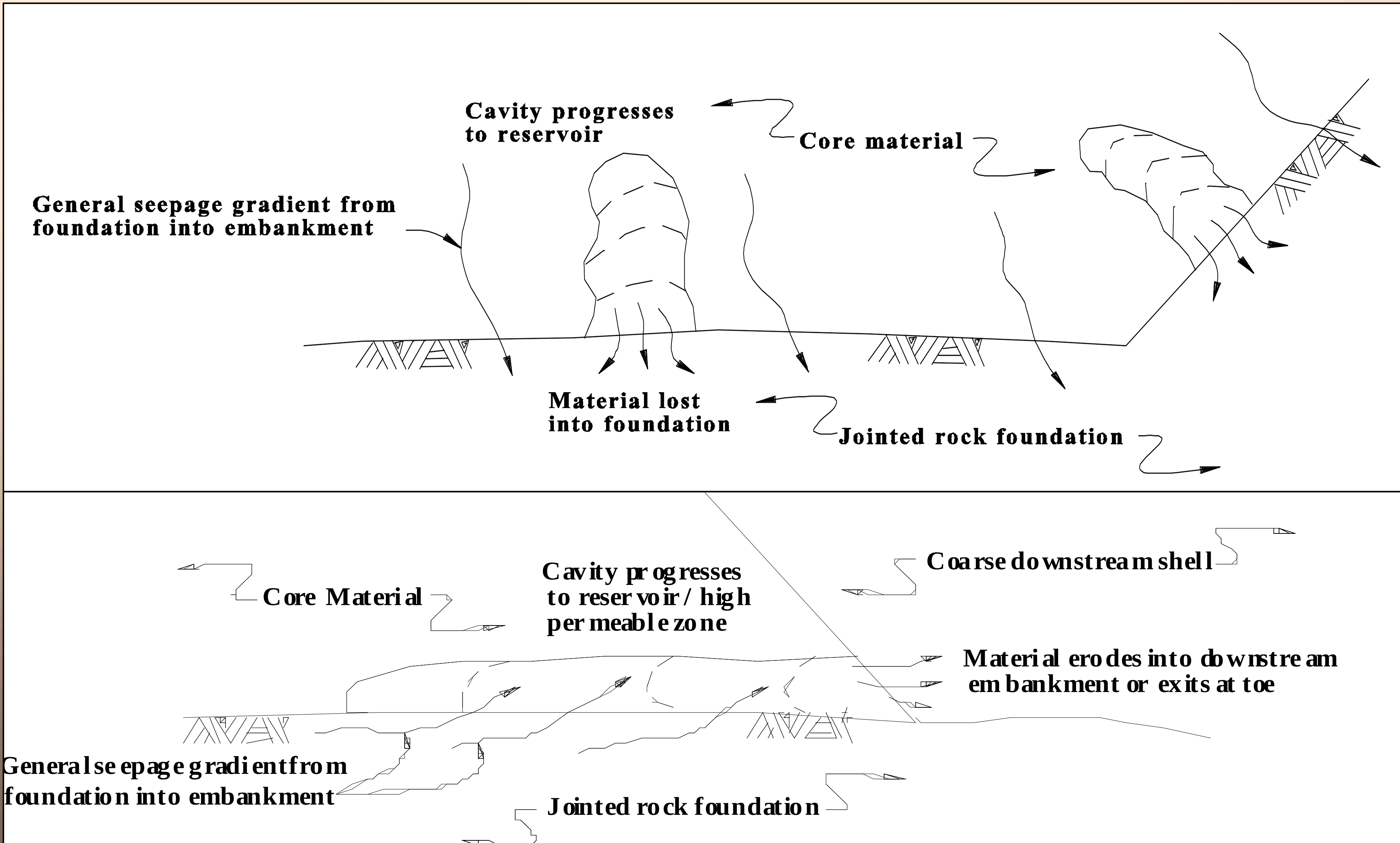
Internal Erosion of Embankment into Foundation



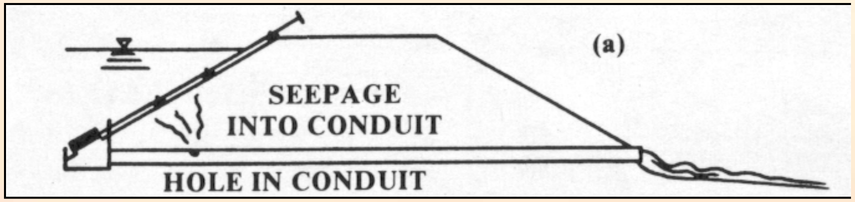
Internal Erosion of Embankment into/along the Foundation

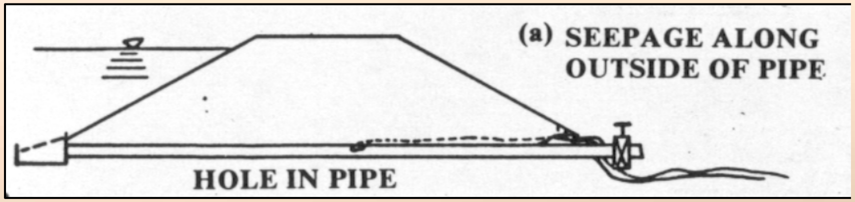
- There are two variations of this category, depending on the location of the seepage path:
  - When the seepage path is primarily in the embankment and the foundation can act as a "drain," there is a potential for embankment soils to be eroded <u>into</u> the foundation soils or rock (if unfiltered exit is present).
  - If the seepage path is primarily through a pervious foundation material <u>along</u> the contact of embankment and foundation, it is more likely that the foundation seepage will attack/erode the overlying core.
- Piezometers can provide key information on which of these is the more likely condition.

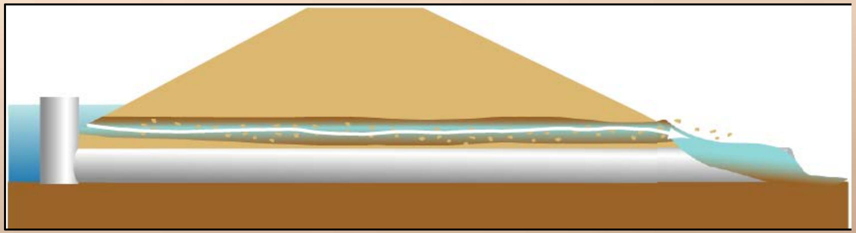
Internal Erosion of Embankment into Foundation: Two Scenarios

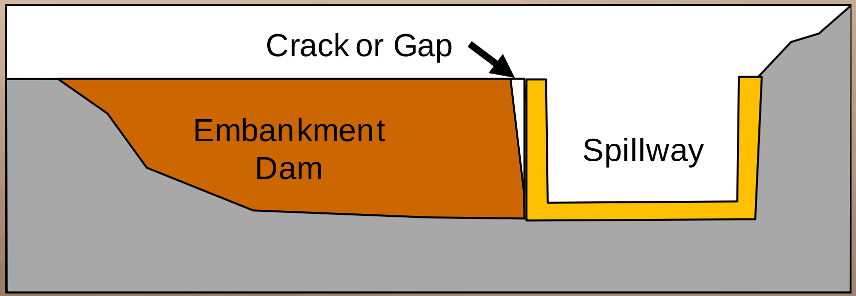


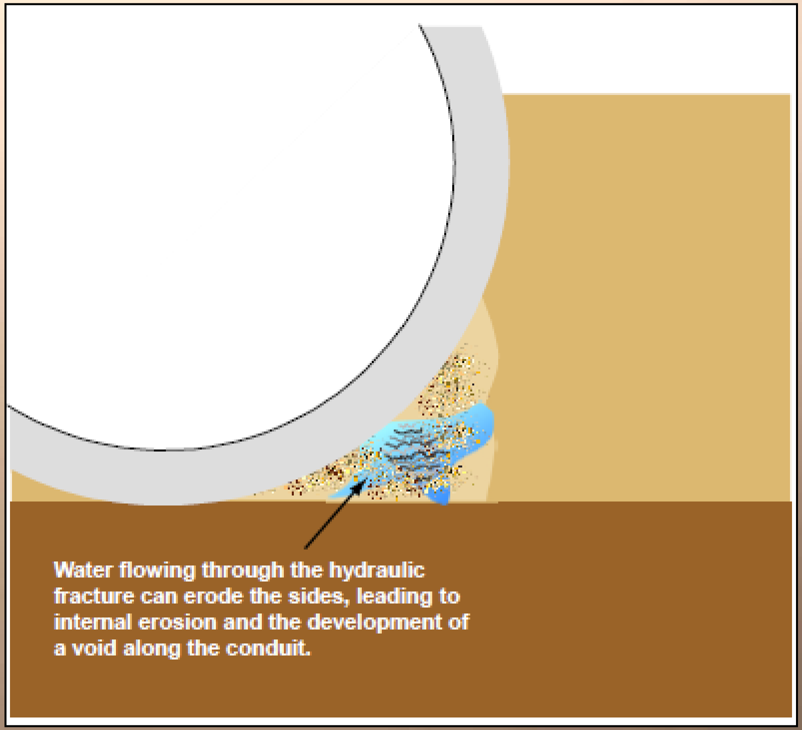
Internal Erosion into/along Structures











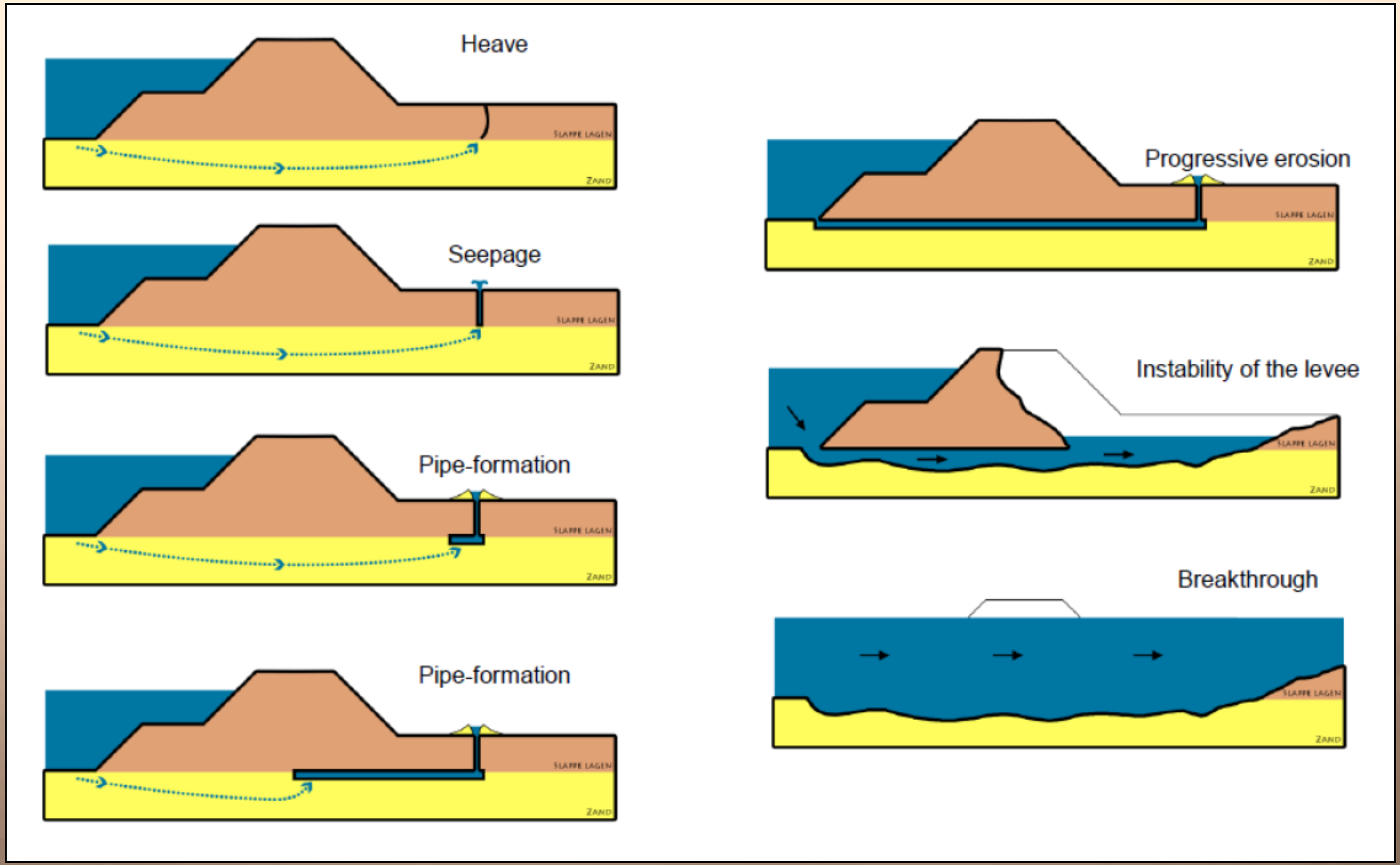
Internal Erosion into Drains

- Reclamation has had a number of incidents of internal erosion into drains:
  - Toe drains
  - Structure underdrains
- Potential for drains to corrode or deteriorate over time explains why this mechanism can be an issue.
- In addition, many older drains were constructed without proper filters surrounding drain pipes.

General Types of Internal Erosion Mechanisms

- There are several different types of internal erosion mechanisms.
- USACE tends to follow the processes as defined by the International Committee on Large Dams (ICOLD).
- Reclamation has adopted slightly different terminology, but considers the same mechanisms.

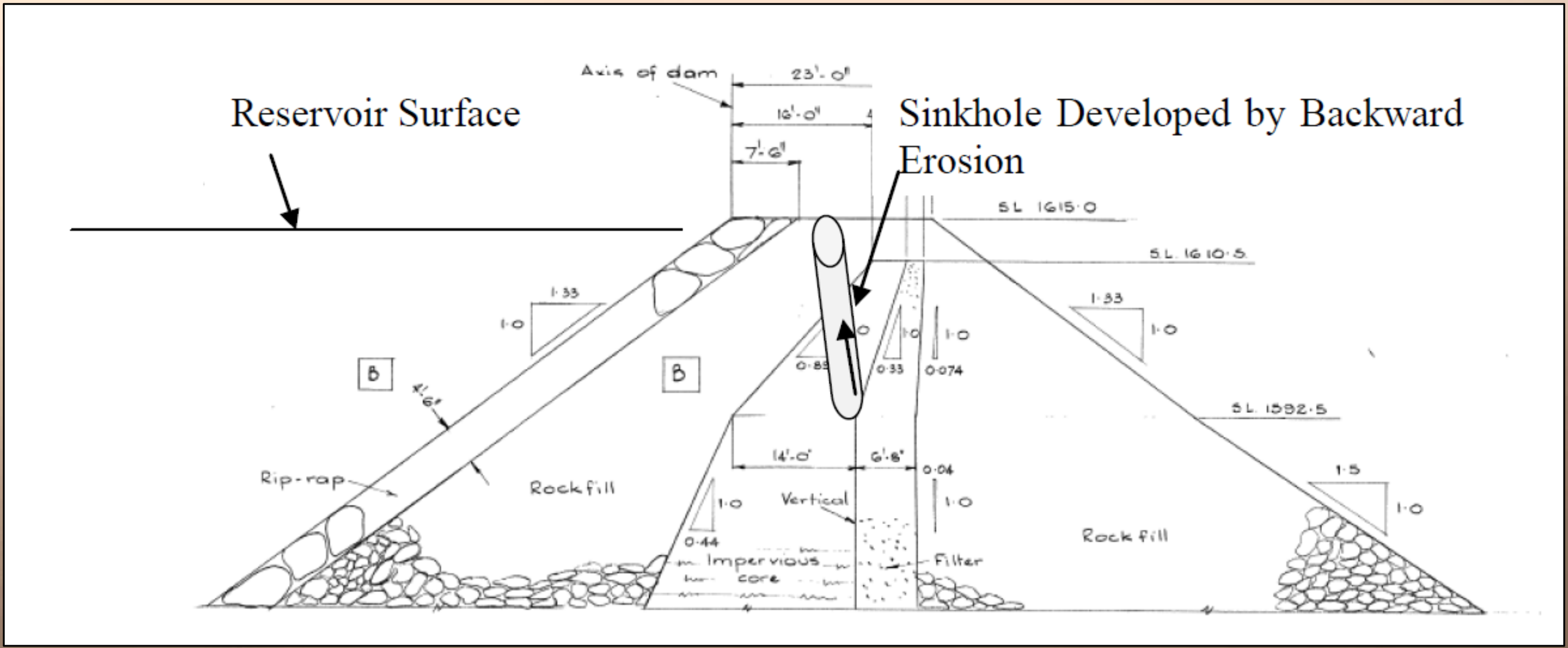
Piping Mechanism



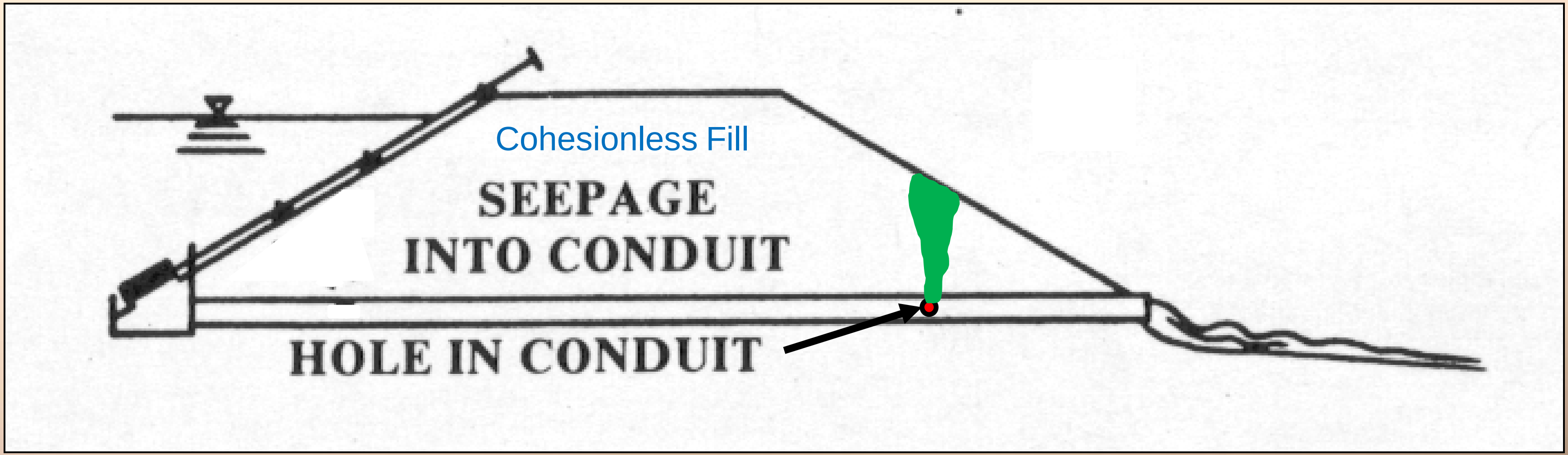
Schematic from van Beek et al. (2010)

Stoping Mechanism

- Also referred to as "internal migration" (Reclamation) and "global backward erosion" (ICOLD)



Stoping Mechanism



Potential Internal Migration into a Crack/Joint in a Conduit

Scour Mechanisms

- Also called:
  - Concentrated leak erosion
  - Contact erosion

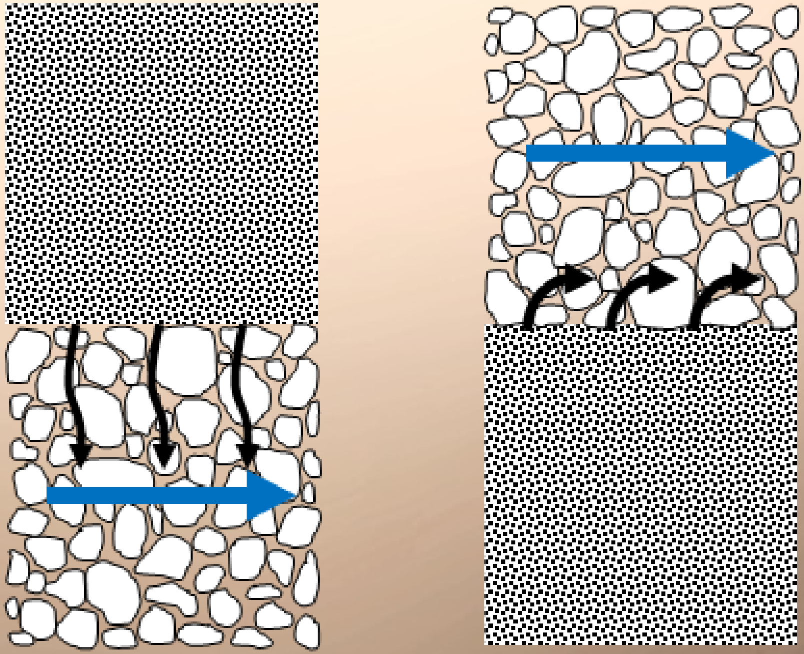
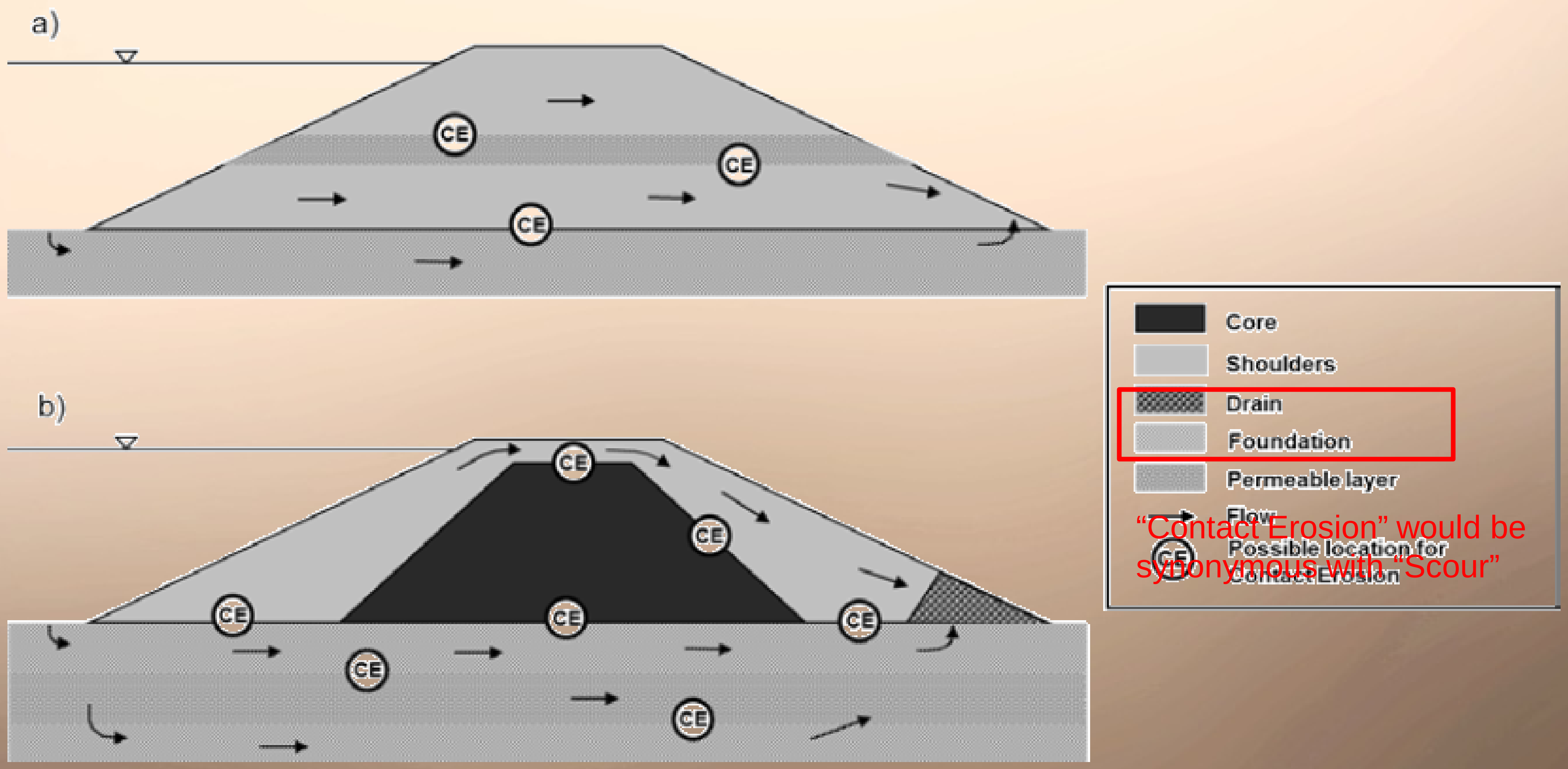


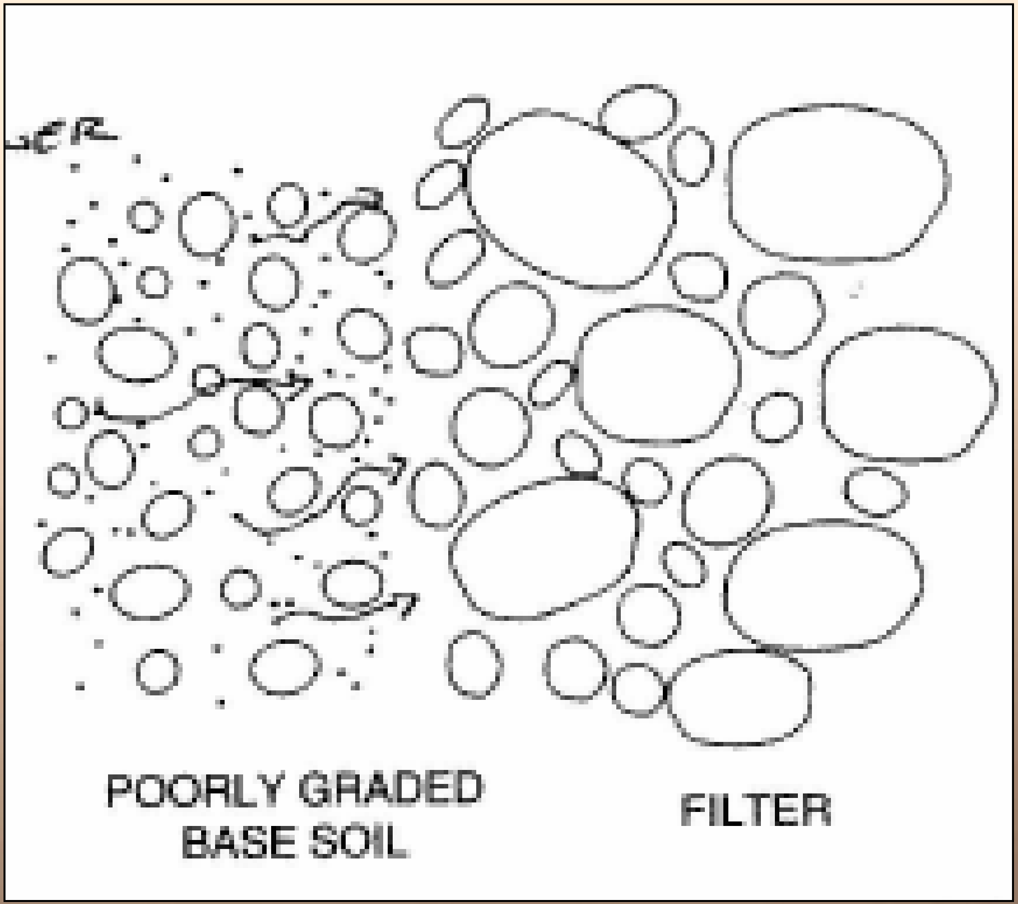
Figure 26-28. Contact Erosion Process (adapted from ICOLD, 2012 Draft)

Contact Erosion Locations



Schematic from Beguin (2011)

Suffusion/Suffosion Mechanisms



Suggested Approach for Evaluating Internal Erosion Risks

- Develop and discuss all potential failure modes
  - Fully describe each PFM
- Develop event trees for each credible failure modes
  - Start with generic and adapt as needed
- Assemble background information
  - Geology, material properties, gradations, instrumentation, design, construction, etc.
- Perform supporting analyses
  - Filter, seepage, stability, gradients; case histories
- Select reservoir load partitions
  - Consider operations, performance, geology, zoning, etc.

Suggested Approach for Evaluating Internal Erosion Risks

- Develop “more likely” and “less likely” factors for each event on the event tree
  - Start with factors on reference tables; add other site-specific factors
- Estimate the probability (and range of uncertainty) for each event
- Perform supplemental evaluations as needed
  - Consider what is driving the potential failure mode; evaluate further as needed
- Evaluate sensitivity
  - Evaluate how sensitive analysis is to a key piece of data

Conceptual Model of Internal Erosion Failure Process

- The internal erosion process can be conceptualized as having 4 general components

INITIATION → CONTINUATION → PROGRESSION → BREACH/FAILURE

INITIATION	CONTINUATION	PROGRESSION	BREACH/FAILURE
Leakage exits the core into the foundation and backward erosion initiates as core erodes into the foundation	Continuation of erosion	Backward erosion progresses to form a pipe. Eroded soil is transported in the foundation	Breach mechanism forms

Conceptual Model of Internal Erosion Failure Process

- Initiation: Refers to the initial movement of soil grains by seepage flows
- Continuation: Refers to the need for an unfiltered exit or "repository" for the internal erosion to continue (or even develop in the first place)
- Progression: Refers to several factors that are needed for erosion pathway to grow or progress (including roof support, flow limiting, self-healing)
- Breach: In the event of unsuccessful intervention, how will the dam fail?

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Typical Event Tree for Risk Analysis (Reclamation)

- Reservoir at or above threshold level
  - Initiation – Erosion starts
    - Continuation – Unfiltered or inadequately filtered exit exists
      - Progression – Continuous stable roof and/or sidewalls
        - Progression – Constriction or upstream zone fails to limit flows
          - Progression – No self-healing by upstream zone
            - Unsuccessful detection and intervention
              - Dam breaches (uncontrolled release of reservoir)

Typical Event Tree for Risk Analysis (USACE)

- Reservoir loading (at or above threshold level)
  - Flaw exists – Continuous crack, high permeability zone, zones subject to hydraulic fracture, etc.
    - Initiation – Particle detachment (erosion starts)
      - Continuation – Unfiltered or inadequately filtered exit exists
        - Progression – Continuous stable roof and/or sidewalls
          - Progression – Constriction or upstream zone fails to limit flows
            - Progression – No self-healing by upstream zone
              - Unsuccessful detection and intervention
                - Dam breaches (uncontrolled release of reservoir)

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Reservoir Rises to Critical Level

- Obviously, the potential for internal erosion is related to the reservoir level (or water surface stage) behind an embankment or levee.
- This initial node is important as it can play a role in several phases of an internal erosion process, including initiation, progression, intervention, and breach.
- Typically, the probability of a given reservoir elevation is determined through the use of reservoir exceedance curves, which are discussed in another portion of this Best Practices class.

Initiation of Internal Erosion

- Initiation
- Continuation
- Progression
- Breach

Erosion Initiates

- This is typically considered the key node in the entire event tree and also probably the most difficult one to estimate.
- It essentially represents the probability that erosion will initiate (i.e., the first grains will start to move)
  - In a given year (Reclamation)
  - Given the loading and a flaw exists (USACE)

Soil Erodibility is a Function of Material Properties

- Plasticity is viewed as the <u>key</u> material property.
  - Internal erosion is simply far more likely to occur in cohesionless (or low plasticity) soils than in cohesive or plastic soils.
- Gradation and particle-size are also important.
  - As particle sizes increase, it takes a higher seepage velocity (more energy) to move soil particles.
- Density plays an important role as well.
  - The denser the soil, the harder it becomes to dislodge the soil particles and initiate erosion.

Piping Potential of Soils (Sherard 1953)

Greatest Piping Resistance Category (1)	1. Plastic clay, (PI > 15), Well compacted.
	2. Plastic clay, PI > 15), Poorly Compacted.
Intermediate Piping Resistance Category (2)	3. Well-graded material with clay binder, (6 < PI < 15), Well compacted.
	4. Well-graded material with clay binder, (6 < PI < 15), Poorly compacted.
	5. Well-graded, cohesionless material, (PI < 6), Well compacted.
Least Piping Resistance Category (3)	6. Well-graded, cohesionless material, (PI < 6), Poorly compacted.
	7. Very uniform, fine cohesionless sand, (PI < 6), Well compacted.
	8. Very uniform, fine, cohesionless sand, (PI < 6), Poorly compacted.

Note: Dispersive soils may be less resistant than Category 3.

Hydraulic Conditions

- Hydraulic gradients and seepage velocities are generally considered the key factors determining the potential for the initiation internal erosion.
- Gradient is easy to measure in the lab; velocity less so. In the field, both are difficult to impossible to measure.
- Hence, "overall" gradients along the entire suspected internal erosion pathway are usually estimated when evaluating internal erosion potential.

Horizontal Gradients

- There is a fundamental difference between upward (vertical) gradients and horizontal gradients.
- While upward (vertical) gradients relate to the potential for heave or uplift, and the possible initiation of internal erosion, horizontal gradients affect the probability that internal erosion can occur.
- Several researchers have measured erosion potential in the lab and determined gradients at which certain soils may erode (in the lab).
- Backward erosion piping may occur at horizontal gradients lower than 0.1.

Stress Conditions

- For our purposes, a discussion of stress conditions that influence the potential for internal erosion to initiate will focus on the presence of defects.
- Frequently, such defects occur from unfavorable stress conditions in an embankment or levee, including:
  - Arching around penetrating conduits
  - Arching around bedrock discontinuities
  - Differential settlement that leads to tension zones and embankment cracking

Defects in Embankments and Foundations

- Cracks
- Arching and low stress zones – hydraulic fractures
- Conduits and other penetrating Structures
- High permeability zones – coarse soils; low density soils
- Bedrock joints and fractures
- Instrumentation installations
- Rodents and vegetation

Defects in Embankments and Foundations

- Basic cause of cracking in embankment dams
  - As an embankment is constructed, the compacted materials consolidate and settlement occurs.
  - Differential settlement is a result of:
    - Differing foundation geometry (rock foundation irregularities, benches, steps, etc.)
    - Differing embankment heights and differing material properties
    - Different foundation materials with different compressibility (including hydrocompression of loess)
    - Stiff elements (conduits) within an embankment
  - Degree of cracking depends on many factors, including the distance over which the differential settlements occur
- Sherard was an early investigator of cracking in dams (see many references).

Defects: Embankment Dam Cracking

- Understanding the types of cracking mechanisms
- Where to look for cracking in embankments:

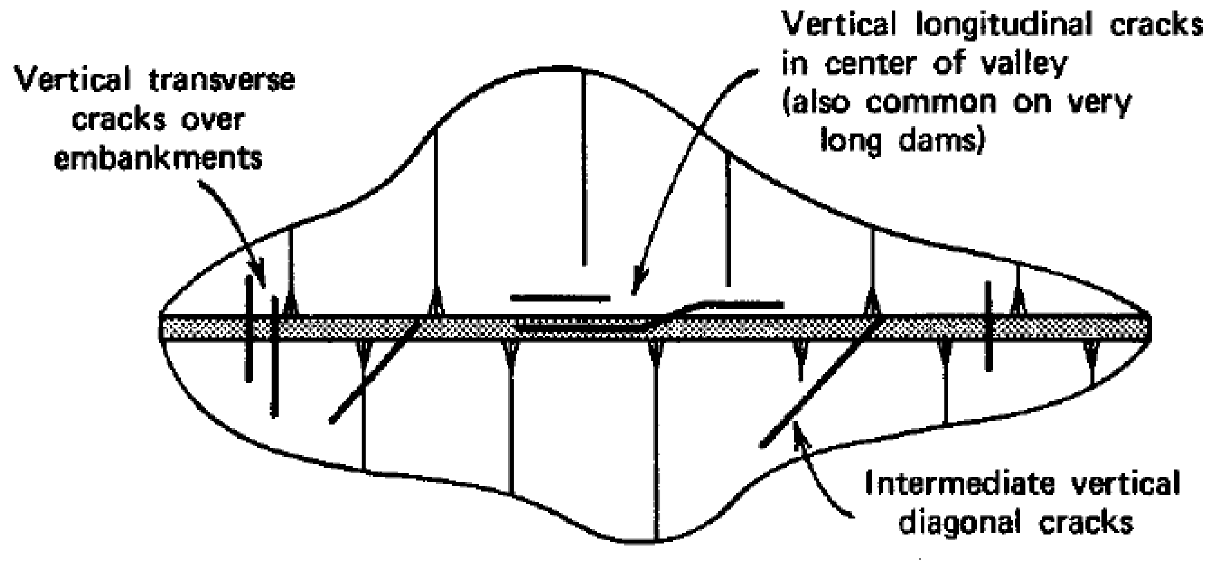


Fig. 20. Common crack patterns in small dams.

(Sherard 1973)

Hydraulic Fractures

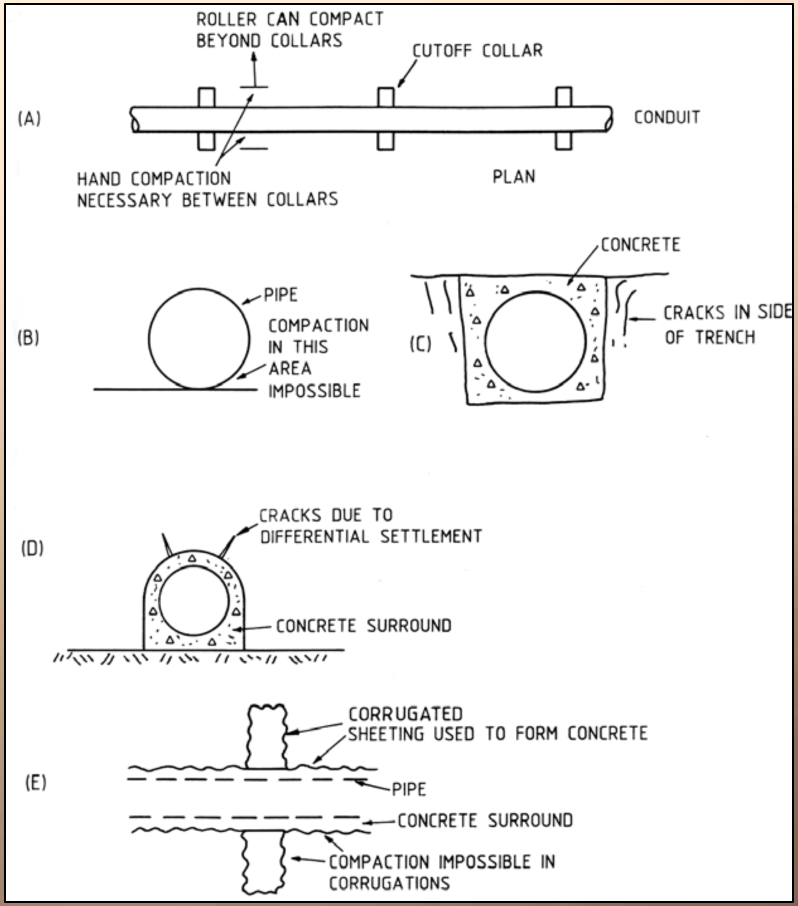
- Hydraulic fractures are formed when hydraulic pressures exceed minor principal stresses (and tensile strength of the soil).
- Hydraulic fractures can occur:
  - In areas of low stress where arching occurs
  - When improper drilling methods are used in the core of the dam
  - Within slurry trench cutoff walls installed as seepage barriers

Hydraulic Fractures

- Sherard (1986) described the process for how a hydraulic fracture forms:
  - In some cases, the fracture never gets wide enough to allow erosion. Depends on flow velocity and erodibility of soils
  - In many cases, the fracture closes as stresses are re-distributed and as materials saturate and expand.
  - Hydraulic fractures held open in cohesive materials for short periods of time after first filling explains why wet spots on the downstream face eventually dry up.

Defects: Conduits through dams

- Causes of internal erosion around conduits (Fell et al. 2004):
  - Inadequate compaction due to cutoff collars
  - Inadequate compaction under the pipe
  - Cracking of soil or weak rock in the sides of trench
  - Cracks due to differential settlement
  - Corrugations or other roughening



Defects: Conduits through dams

- Problems with seepage collars (FEMA 2005)

Figure 17.—Failure of an embankment dam following first filling. The failure was attributed to internal erosion because the time required for seepage to develop through the compacted embankment and cause failure was very short. Also, the soils are not the type ordinarily considered susceptible to backward erosion piping. Antiseep collars were not effective in preventing the failure.

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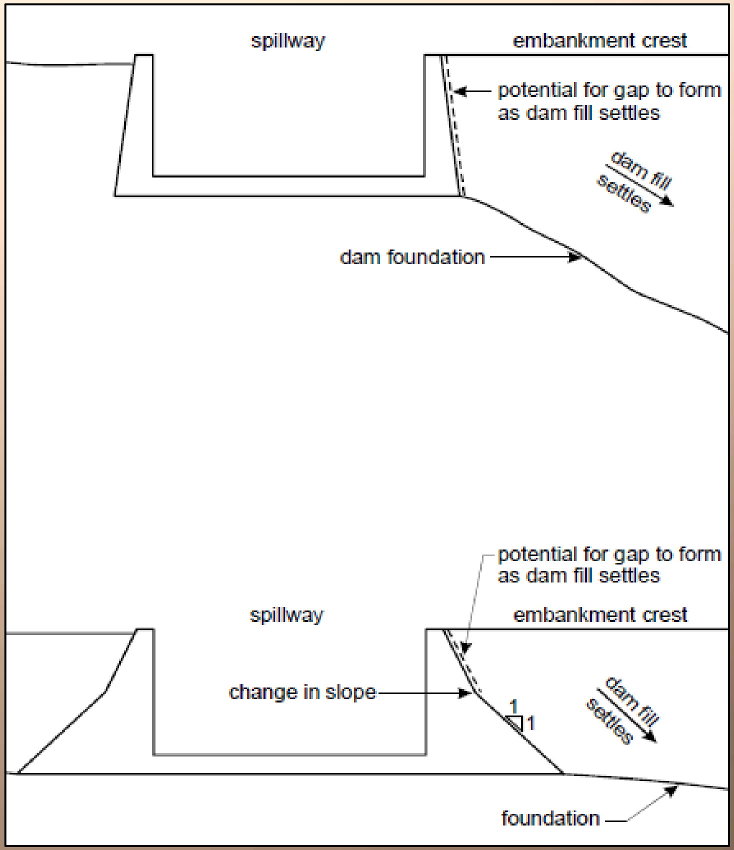
Defects: Conduits through Dams

- Factors increasing the likelihood of developing problems with conduits (FEMA 2005)
  - Abrupt changes in foundation conditions (differential settlement)
  - Circular conduits without proper bedding
  - Conduits with an excessive number of joints
  - Excavations that remove unsuitable foundation materials under the conduit can lead to differential settlements
  - Compressible foundations
  - Embankment materials susceptible to internal erosion
  - Inadequate compaction around conduits
  - Conduits constructed of materials susceptible to deterioration (CMP)
  - *Conduits constructed without a filter collar or filter diaphragm*

Defects: Spillway Walls

- Locations where a crack or gap could form between the dam and a spillway wall (Fell et al. 2004):
  – Steep foundation adjacent to spillway wall
  – Change in geometry of wall



Defects: High Permeability Zone

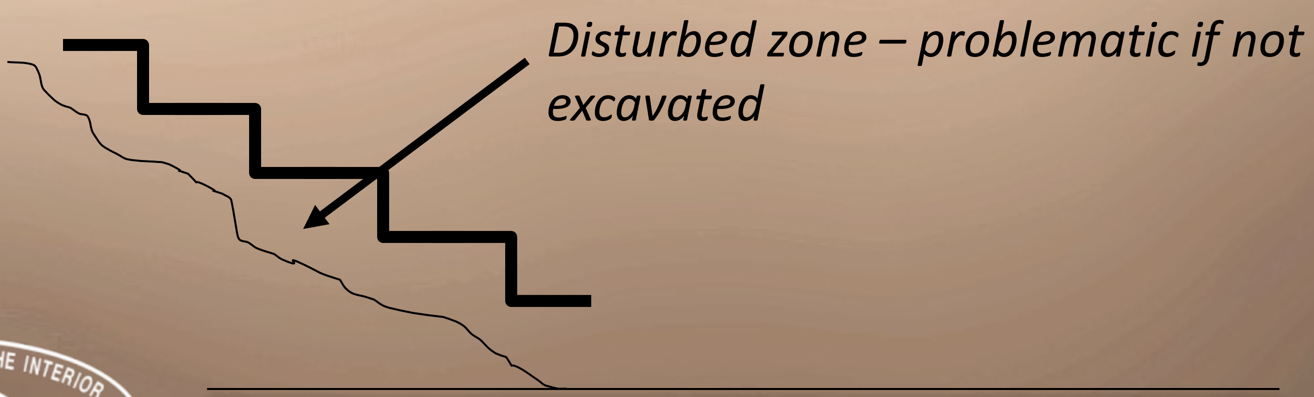
- Possible causes:
  - Poor compaction (low density, thick lifts, water content):
    - Low density, poor QC, smaller equipment
    - Thick lifts, poor QC, rush construction
    - Water content problems, or no effort to use water
    - Water conditioning effectiveness on fill versus in borrow area
  - Layers of coarse soil:
    - Borrow area development (fining upward sequence)
    - Variable borrow (best materials are used first)
    - Multiple borrow areas
    - Segregation issues
  - Poor treatment at foundation contact

Defects: High Permeability Zone

- Possible causes:
  - Winter construction and winter shutdown:
    - Ice lenses; decreased density. Was sacrificial lift placed?
    - Lifts exposed to weather and precipitation
    - Special efforts for winter climates
  - Desiccation during construction:
    - Construction during hot, dry seasons
    - Lifts dry out and crack.
  - Embankment placed against structures such as walls and conduits
    - More difficult to compact
    - Special compaction (hand efforts and equipment), typically not as effective as large equipment

Defects: High Permeability Zone

- Possible causes:
  - Closure section
    - Fill slope exposed to weather and precipitation for period of time
    - Could have high permeability if proper treatment of fill was not performed



Foundation Defects

- Bedrock defects can include bedrock joints, fractures, bedding planes, foliation, shears, faults.
- The term "discontinuities" used to describe these defects.
- Sources of bedrock defects can include:
  - Stress relief joints in valley sides (Fontenelle Dam)
  - Stress relief in valley floor
  - Karst features in limestone, dolomite, gypsum
  - Defects associated with landslides, faults, shear zones

Foundation Defects

- Factors to consider:
  - Widths of defects (controls flow rate and size of particles that can be transported)
  - *Continuity of bedrock defects*
  - Site topography and geology (fairly well-know for Reclamation dams)
  - Geology (strike and dip directions)
  - Quality and quantity of subsurface information
  - Understanding of the subsurface information
  - Construction records related to foundation treatment; specifically grouting and surface treatment
  - Presence of shales and treatment for slaking

Foundation Defects

- Factors to consider:
  - Joint infilling and soil type
  - Effectiveness of bedrock grouting (if any)
  - Effectiveness of cutoff walls (if any)
  - Effects of blasting during construction:
    - Temporary diversion
    - Cutoff construction
    - Outlet conduit construction
  - Unique geologic features in contact with embankment, including the base of a cutoff trench
  - Surface treatment (if any) and shaping can be the defect.

Foundation Defects

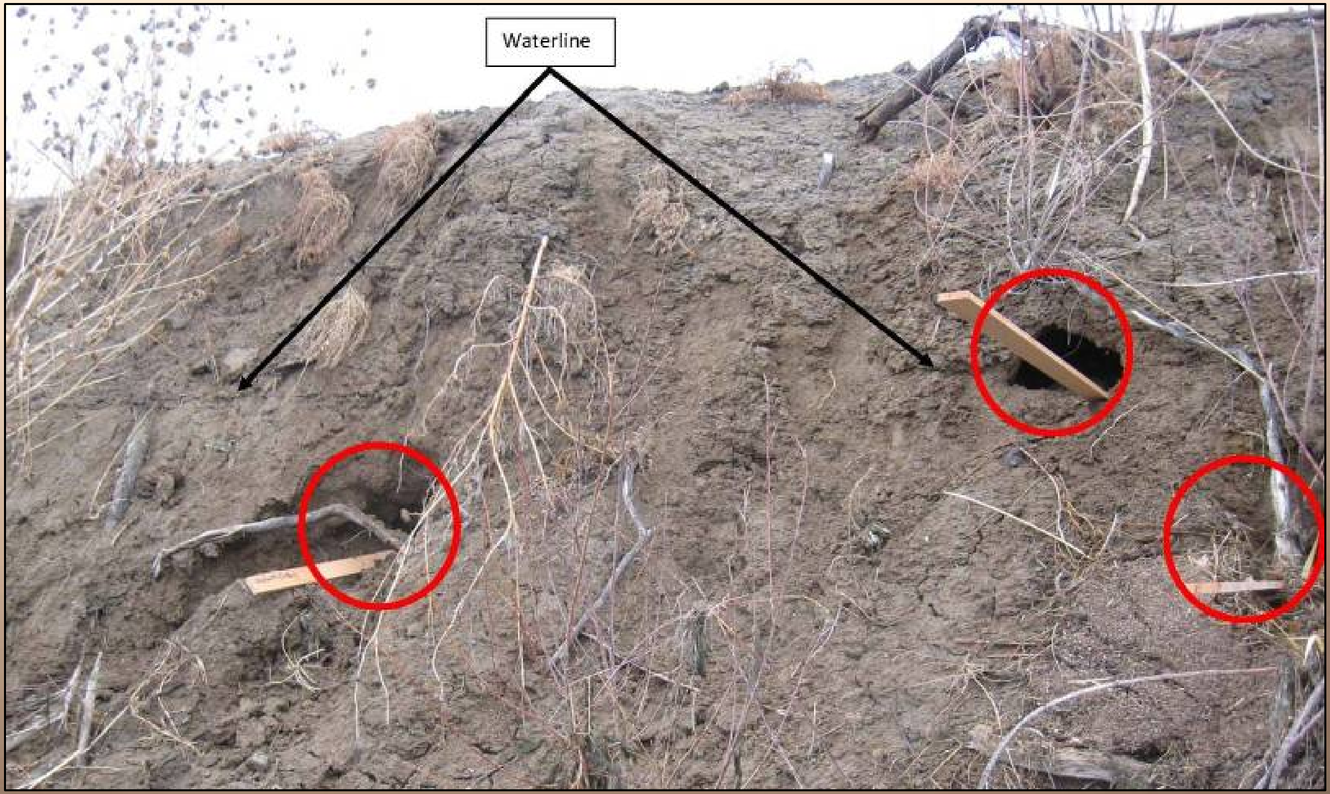
- Karst or solution features considerations:
  - Mechanical erosion of the in-filling is typically the main concern
  - Less concern with solutioning of rock
  - Erosion of ancient sinkholes with in-filled breccia
  - Highly dependent on the geologic environment
  - Consider topography (e.g., sinkholes, caves)
  - Consider regional continuity and trend. Do local features align upstream-downstream across the dam?

Foundation Defects

- Soil foundations: factors to consider:
  - Is the dam founded on landslide materials or talus?
  - Is there a continuous upstream to downstream layer of cohesionless material?
  - Is the material erodible? Is the PI less than 7?
  - Is the continuous layer beneath a confining layer at the downstream toe? If so, consider blowout.
  - How thick is the confining layer? Are there defects in the confining layer (cracks, sandy zones, vegetation roots, animal burrows, manmade penetrations)?
    - Lesser chance of defects with thicker layers.

Animal Burrows

- Typically, more of concern on canals and levee embankments (smaller structures) than dams



Estimating the Probability of the Initiation of Internal Erosion

- Different agencies approach the estimation of the probability that internal erosion will estimate in different ways.
  - Reclamation relies primarily on the use of historical "base rate frequencies" developed from the number of incidents observed in the nearly 100 years of dam operation.
  - USACE looks at a variety of studies, research, and analyses to gain an understanding of the potential that internal erosion may initiate for the given conditions at the dam being evaluated, as well as base rates.
- Both approaches are discussed in the chapter.

USBR - Proposed Best Estimate Values of Annual Probabilities of Initiation of Internal Erosion by Category

Category of internal erosion	Range of initiation probability
Embankment only	$3x10^{-4}$ to $1x10^{-3}$
Foundation only	$2x10^{-3}$ to $1x10^{-2}$
Embankment into foundation	$2x10^{-4}$ to $1x10^{-3}$
Into/Along conduit	$4x10^{-4}$ to $1x10^{-3}$
Into drain	$5x10^{-4}$ to $2x10^{-3}$

Note: All 4 internal erosion mechanisms are included in this compilation.

USACE Tools for Estimating the Probability of Initiation

- For concentrated leak erosion:
  - Evaluation of “critical shear stress” from Hole Erosion Tests (HET) and Jet Erosion Tests (JET)
  - Evaluation of “hydraulic shear stress” in cracks based on UNSW testing
- For contact erosion:
  - Cyril et al. (2010) approach to critical velocity

USACE Tools for Estimating the Probability of Initiation

- For backward erosion piping:
  - Kovacs (1981) work on the critical exit gradient
  - Terzaghi and Peck (1996) discussion of piping by heave
  - Sellmeijer et. al. (2011) research (Delft/Deltares testing) on horizontal gradient
  - Schmertmann (2000) research on horizontal gradient

USACE Tools for Estimating the Probability of Initiation

- For suffusion:
  - Sherard (1979) approach to internal instability
  - Burenkova (1993) work on internal instability
  - Wan and Fell (2004) research/testing on suffusion at UNSW

Use of Tables

- For either approach, risk estimating teams are encouraged to use the table of “more likely” and “less likely” factors included at the end of the chapter.
- These tables provide a number of factors that make each step of the internal erosion process more likely or less likely to occur.
- The tables represent a compilation of the findings and judgment from many researchers, as well as findings from empirical cases related to the development of each phase of internal erosion.

Continuation: Filters and Unfiltered Exits

- Initiation
- Continuation
- Progression
- Breach

Continuation

- Typically, the second phase of the internal erosion process in which an open, unfiltered, or inadequately filtered exit allows erosion of the embankment or foundation materials to continue.
- When considering the potential for continuation at a particular dam, the downstream embankment zones and foundation materials are evaluated to assess their ability to provide filtering.

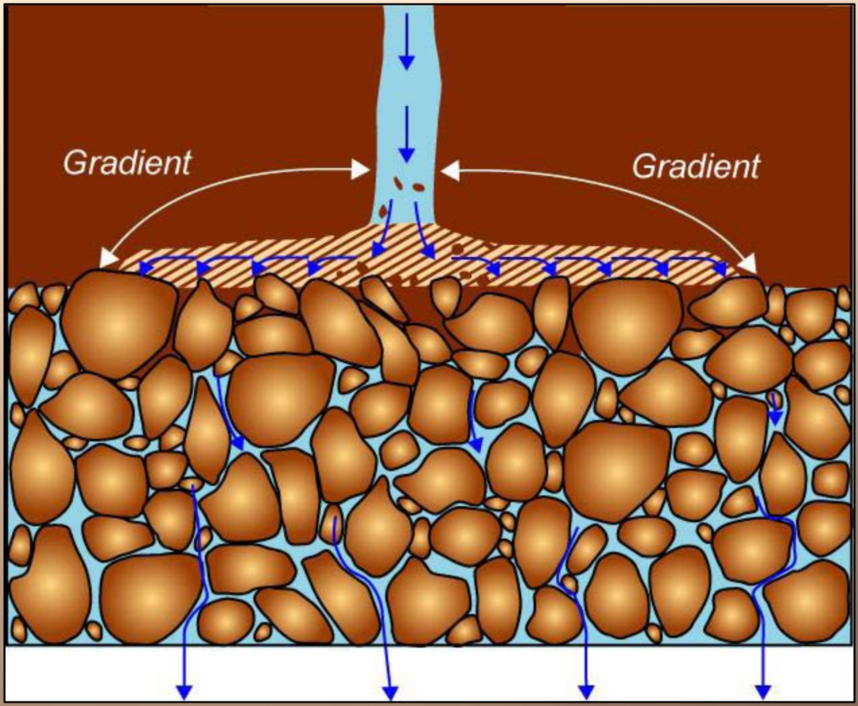
Particle Retention Criteria for Filters and Base Soil Categories

- Notes:
  - Re-grade base soil on No. 4 sieve
  - Criteria not sufficiently conservative for dispersive soils

Base Soil Category	Fines Content (percent)	Criteria for No Erosion Boundary
1	$FC > 85$	$D_{15}F \leq 9(D_{85}B)$
2	$40 < FC \leq 85$	$D_{15}F \leq 0.7$ mm
3	$15 < FC \leq 40$	$D_{15}F \leq (4(D_{85}B) - 0.7)\left(\frac{40 - FC}{25}\right) + 0.7$ If $4(D_{85}B) < 0.7$ mm, use $D_{15}F \leq 0.7$ mm.
4	$FC \leq 15$	$D_{15}F \leq 4(D_{85}B)$

How a filter works to prevent internal erosion in event of a flaw

- Eroding soil is caught at the filter face. Hydraulic fracturing from the high gradients between water in the crack and the filter causes further widening of the cake on the filter until the gradient is reduced. The very low permeability filter cake covers the width of the crack and some distance on each side. The remaining filter is open for collecting seepage flow through the pores of the soil between cracks.



Filters That Do Not Meet Modern Filter Design Criteria

- What if filter is coarser that required by modern filter criteria?
- Foster and Fell (2001) developed concept of some erosion, excessive erosion, and continuing erosion.
  - Function of amount of particle retention and how much erosion occurs before the erosion process stops.
  - Developed with the use of the continuing erosion filter test.

Foster and Fell (2001) Criteria

- No erosion: The filtering material stops erosion with no or very little erosion of the base material.
- Some erosion: The filtering materials initially allow erosion from the soil it is protecting, but it eventually seals up after some erosion.
- Excessive erosion: The filter material allows erosion from the material it is protecting, but after excessive erosion of base soils. The extent of erosion is sufficient to cause sinkholes on the crest and erosion tunnels through the core.
- Continuing erosion: The filtering material is too coarse to stop erosion of the base material and continuing erosion is permitted. Unlimited erosion and leakage flows are likely.

Excessive/Continuing Erosion Criteria

Base Soil	Criteria for Excessive Erosion Boundary
$D_{95}B \leq 0.3$ mm	$D_{15}F > 9(D_{95}B)$
$0.3 < D_{95}B \leq 2$ mm	$D_{15}F > 9(D_{90}B)$
$D_{95}B > 2$ mm and $FC \leq 15$ percent	$D_{15}F > 9(D_{85}B)$
$D_{95}B > 2$ mm and 15 percent $< FC \leq 35$ percent	$D_{15}F > 2.5\left((4(D_{85}B) - 0.7)\left(\frac{35 - FC}{20}\right) + 0.7\right)$
$D_{95}B > 2$ mm and $FC > 35$ percent	$D_{15}F >$ ($D_{15}F$ value for erosion loss of $0.25 g/cm^2$ in the CEF test, as shown in Figure 26-34)
Notes: Criteria are directly applicable to soils with $D_{95}B$ up to 4.75 mm. For soils with coarser particles, determine $D_{85}B$ and $D_{95}B$ using gradation curves adjusted to give a maximum size of 4.75 mm.	

- Continuing erosion criterion:
  - For all soils, $D_{15}F > 9(D_{95}B)$

(Foster and Fell 2001)

Continuation: Unfiltered Exit Other Considerations

- Filter width
- Internal instability
- Segregation
- Cohesion and cementation

Filter Width

- Theoretical minimum width or thickness for filter designed according to “no erosion” criteria is very small and does not control the dimension of filters.
- Width of filter is often dictated by construction considerations.
- The wider the filter, the less potential for a continuous “flaw”
  - “Flaw” could result from segregation, construction issues, cracking, cohesion or cementation, or other
- Two-stage filters perform better than one-stage filters.

Internal Instability of Filters

- Suffusion of filter material:
  - Fine fraction erodes out of a filter material leaving a coarser filter which is not compatible with the base soils (increases effective $D_{15}F$).
  - When the filter can no longer retain base (core) materials, the core may be transported through the filter, resulting in internal erosion.
  - Segregation of filter material could result in internal instability.

Segregation of Filter Material

- Undesirable construction practices:
  - Dropping filter materials into piles or windrows from front-end loaders, trucks, or other equipment
  - Using conveyor belts to dump filter materials on stockpiles
  - Loading materials into hauling units from a chute
  - Loading materials into hauling units from a hopper

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Segregation of Filter Material

- Concern is the potential for coarse-grained layers that do not meet filter criteria that are continuous or sufficiently large to act as a repository
- Broadly graded materials, particularly with a maximum particle size > 75 mm
- Low percentage of sand and fine gravel sizes (< 40% finer than 4.75 mm)

Cohesion and Cementation

- Key concern is whether the filter or zone immediately downstream of impermeable zone will collapse in event of pipe or crack
- Achieved by:
  - Limiting fines content to 5% or less
  - Requiring fines be non-plastic
  - Testing for cementation agents
- Concerns:
  - Cementing of filters may occur if filter composed of carbonate particles such as limestone or dolomite
  - Cementation or cohesion can reduce ability of filter to slump, fill cracks, and protect core of the dam
  - Cementation or cohesion can clog pores and reduce permeability

Progression

- Initiation
- Continuation
- Progression
- Breach

Progression

- Progression is the process of developing and enlarging an erosion pathway through the embankment or foundation.
- Is there some condition that exists or a process that could occur to stop the erosion?

Progression

- Progression phase is typically considered by evaluating three events (or processes) that could occur:
  - Continuous stable roof and/or sidewalls: Does a continuous, stable roof (or sidewalls) develop through the core or foundation?
  - Constriction or upstream zone fails to limit flows: Will flows be limited sufficiently to prevent the erosion path from increasing in size?
  - No self-healing by upstream zone: Will materials from an upstream zone provide "self-healing" (i.e., form a filter) at the unfiltered exit?
- Slightly modified order and wording

Progression

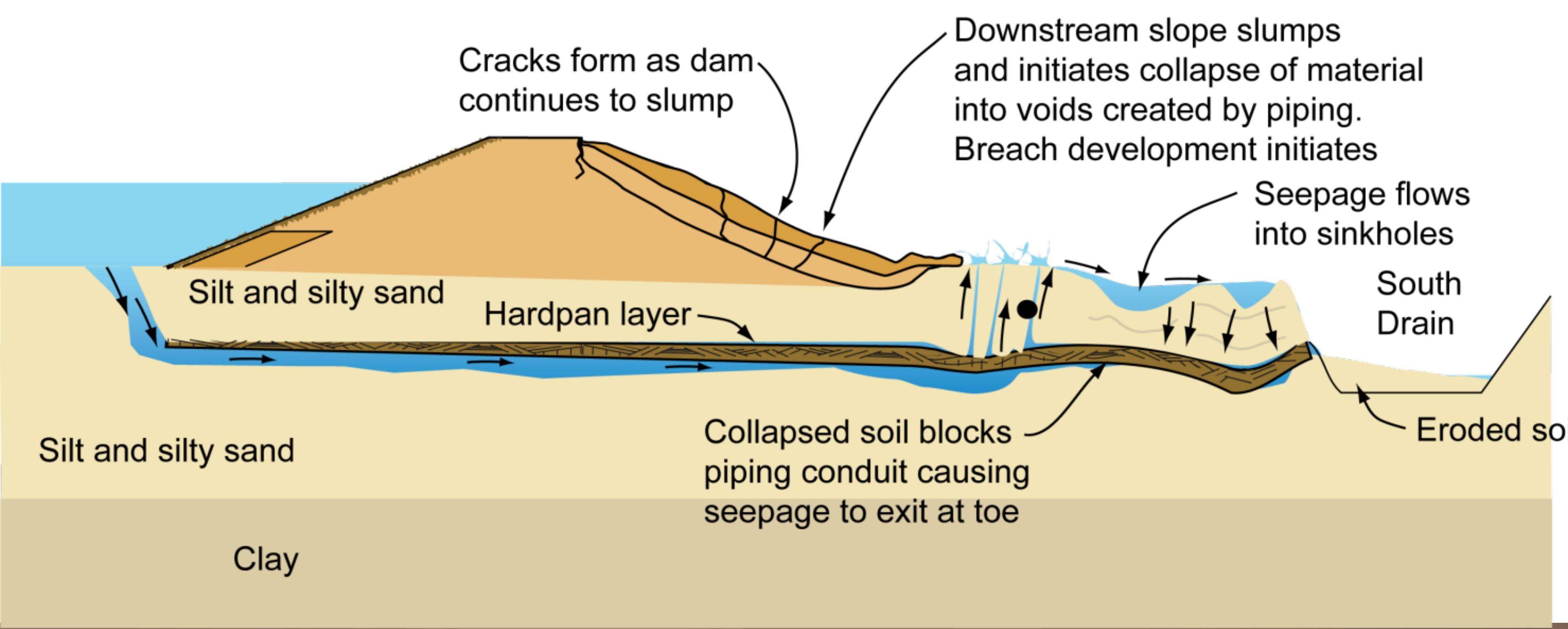
- These three progression events do not necessarily occur in a linear progression (e.g., roof could be initially stable, but collapses when the pipe enlarges after flow limiting was unsuccessful).

Continuous Stable Roof/Sidewalls

- Primary consideration is whether a <u>continuous</u> hard layer or stiff zone exists in the embankment or foundation above the eroding materials under consideration.
  - Concrete structures such as conduits, spillways or walls can serve as a roof.
  - Hardpan, caliche, basalt, or stiff clay in the foundation can serve as a roof.
  - Absent a continuous structure or hard layer, the ability to sustain a roof depends mainly on soil properties of the eroding soil (core or foundation).

Hardpan at A.V. Watkins Provided a Roof

- Continuous hardpan exists from South Drain to upstream of the dam



Guidance for Probability of Stable Roof and/or Sidewalls

USCS Soil Classification	Fines Content, FC (percent)	Plasticity of Fines	Moisture Condition	Probability of Holding a Roof (P_{PR})
Clays, sandy clays (CL, CH, CL-CH)	FC ≥ 50	Plastic	Moist or Saturated	0.9+
Silts (ML, MH)	FC ≥ 50	Plastic or Non-Plastic	Moist or Saturated	0.9+
Clayey sands, gravelly clays (SC, GC)	15 ≤ FC < 50	Plastic	Moist or Saturated	0.9+
Silty sands, silty gravels, silty sandy gravel (SM, GM)	15 ≤ FC < 50	Non-Plastic	Moist Saturated	0.7 to 0.9+ 0.5 to 0.9+
Granular soils with some cohesive fines (SP-SC, SW-SC, GP-GC, GW-GC)	5 ≤ FC < 15	Plastic	Moist Saturated	0.5 to 0.9+ 0.2 to 0.5
Granular soils with some non-plastic fines (SP-SM, SW-SM, GP-GM, GW-GM)	5 ≤ FC < 15	Non-Plastic	Moist Saturated	0.05 to 0.1 0.02 to 0.05
Granular soils (SP, SW, GP, GW)	FC < 5	Plastic	Moist or Saturated	0.001 to 0.01
		Non-Plastic	Moist or Saturated	0.0001

Constriction or Upstream Zone Fails to Limit Flows

- Considers upstream zone or flow constriction at any point along the path that could prevent further progression of erosion
- Flow limitation can potentially result in an equilibrium between flow velocity (forces tending to erode the soil) and the ability of the soil to withstand the erosion, so the erosion process could stabilize. Expressed another way,

Eroding Forces ≤ Resisting Forces = Progression Stops

Constriction or Upstream Zone Fails to Limit Flows

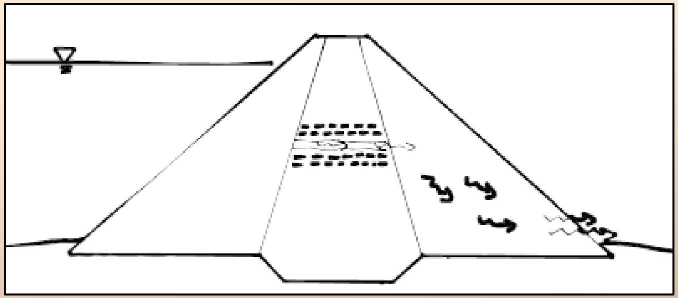
- Teton Dam foundation conditions (and lack of surface treatment) are extreme.
- Fontenelle Dam also had similar foundation conditions, but progression (and breach process) occurred more slowly due to much smaller bedrock discontinuities.
- Progression phase of the process can allow time for successful intervention as occurred at Fontenelle Dam.

Teton Dam

Fontenelle Dam

No Self-healing by Upstream Zone

- Are upstream zone materials capable of being transported to a downstream zone or constriction (such as a bedrock joint) where a filter could form sufficient to prevent further erosion of the core?



No benefit to this node if no downstream zone or constriction exists

- Favorable characteristics of upstream zone:
  - Coarse, clean, cohesionless upstream materials with wide range of particles sizes
  - Large volume of upstream materials
  - Presence of a downstream zone that can provide a “stop” for the upstream materials that are carried through the core

Intervention

- This single event in the event tree evaluates the potential that two components might occur:
  - Detection: Whether, or when, a developing failure mechanism would be observed and recognized as a problem
  - Ability to successfully intervene: Can mitigating efforts be implemented in time to stop or slow the failure process to the point where dam breach does not occur?
- In the event tree it is located just before breach, but it is understood that intervention could occur at any time.
- Case histories suggest that the dam/levee safety community has effectively intervened in a large number of incidents.

Intervention Factors to Consider

- Primary factors are typically site-specific: input from dam operator, water district, area and regional office representatives can be very useful.
- "Eyes on the dam" considerations:
  - Is the dam in a remote location?
  - Are likely exit paths observable (rockfill, tailwater, marsh, vegetation)?
  - How often is the dam visited by USACE or Reclamation staff?
    - Consider seasonal variations
    - Power generation facilities versus irrigation projects
  - Public considerations: How close does the public get?
    - Are they likely to report unusual behavior?
  - State/local parks and recreation officials: Dam safety trained?

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Intervention Factors to Consider

- Detection through instrumentation and observations:
  - It is unlikely a piezometer or seepage weir is located exactly at the location of a concentrated leak or developing failure mode.
  - Over long-term, piezometer and seepage measurement trends *can be* indicative of slowly developing internal erosion failure modes.
  - Often, it is changes in behavior from visual observations that provide the earliest indicators of a developing internal erosion failure mode.
  - Seepage observations of internal erosion failure modes in progress tend to be episodic (large changes in behavior; both increasing and decreasing) at different observation times.
    - Consistent trends are not always present.

Primary Factors for Evaluating the Ability to Stop the Erosion Process

- Access: Can large equipment be mobilized to areas of the dam where internal erosion is likely to develop?
  - Are there good access roads around the site?
  - Consider bridge limitations, especially spillway bridges
  - Alternate routes to opposite abutment areas
  - Consider crest width
  - Steepness of embankment slopes
  - Wet or marshy downstream areas can limit equipment access

Primary Factors for Evaluating the Ability to Stop the Erosion Process

- Practicality: Is it realistic and possible?
  - How do you intervene for a downstream rockfill zone?
    - Practicality of placing a weighted filter berm over rockfill
    - Difficult access on steep 2H:1V rockfill slope
  - What if the upstream entrance point is deep under water?
  - What if the downstream exit point of a through the foundation PFM is high on the abutment? What if the abutment is steep, or very difficult access?

Primary Factors for Evaluating the Ability to Stop the Erosion Process

- Material availability:
  - Is there a nearby source of sand and gravel (or even larger rock)? On-site would be the most ideal.
  - Are pre-established agreements in place with local material suppliers?
  - Can embankment material be cannibalized? Length of dam and freeboard considerations.
  - Keep in mind the volume of needed materials to stop erosion in-progress is significant (likely hundreds of cubic yards).

Primary Factors for Evaluating the Ability to Stop the Erosion Process

- Equipment availability
  - How quickly can excavators, loaders, dozers, dump trucks be mobilized to the site?
  - Does the local water district or sponsor have equipment available for use?
  - Are pre-established agreements in place with local contractors?
  - Perhaps local office might have such agreements.

Intervention Factors to Consider

- Release capacity and size of reservoir
  - Can the reservoir be drawn down?
  - What is the likelihood that sufficient volume could be released (or head lowered) before a full breach develops?
  - Consider if outlet works is part of the failure mode
- Amount of freeboard
  - Lower reservoir: easier to access upstream portions
  - Higher reservoir: intervention could be more difficult because of higher gradients and greater head

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Considerations for Estimating and Reporting Probability

- Even with a high historical success rate, there are significant unknowns, and risk teams are sometimes reluctant to put too much faith in intervention.
- Probabilities of initiation and continuation often tend to drive the risk estimate.
- It is USACE practice to estimate annual probability of failure both with and without considering intervention.

Breach

- Initiation
- Continuation
- Progression
- Breach

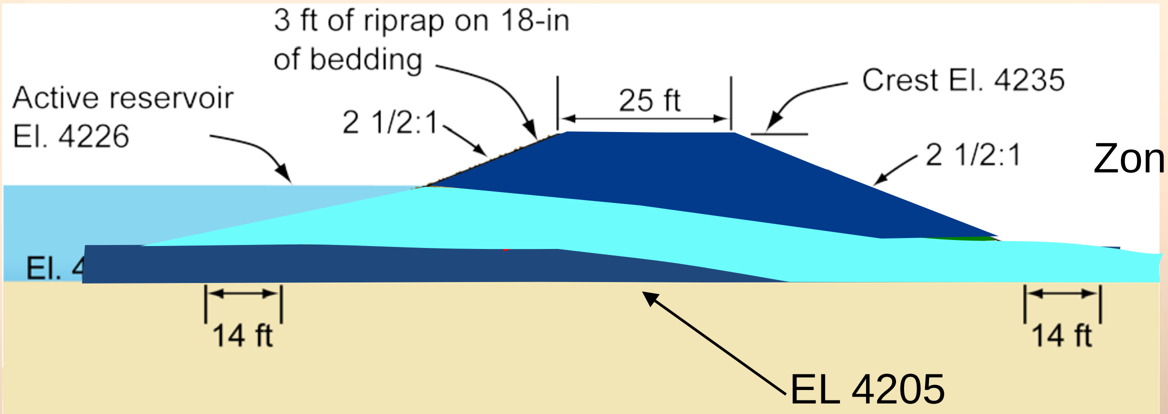
Breach

- Important to understand how the dam might breach for the potential failure mode under consideration:
  - <u>Gross enlargement</u> of a pipe or concentrated leak followed by collapse of the embankment, loss of freeboard, and overtopping
  - <u>Sloughing or unraveling</u> of the downstream slope due to high seepage flows resulting in an over-steepened slope that progressively works toward the reservoir
  - <u>Sinkhole development</u> sufficiently large to drop the crest below reservoir level or disrupt it enough so that it can no longer retain the reservoir
  - <u>Slope instability</u> resulting from increased foundation or embankment pore pressures caused by internal erosion

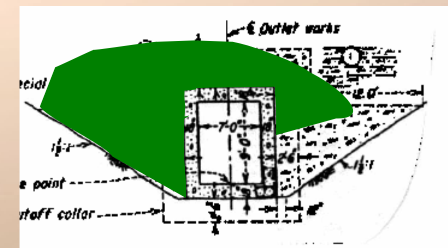
Breach

- Type of breach depends on internal erosion process being considered, embankment type, and the specific failure mode being considered.
  - A potential failure mode is usually dominated by one or two breach mechanisms.
  - Risk estimates should typically be developed considering the most likely breach mechanism(s).
- Breach mechanisms vary in their time to fully develop and catastrophically release the reservoir, and the intervention node should consider the potential time available based on breach mechanism being considered.

Breach by Gross Enlargement



Zone 1A

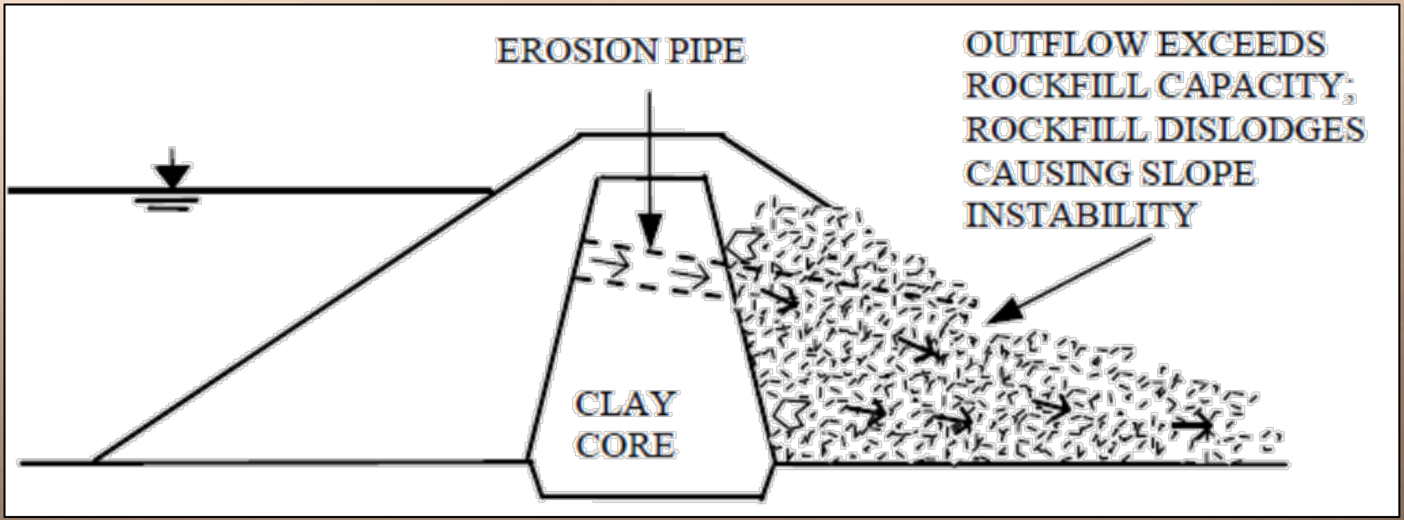


Internal Erosion along the Outlet Works Conduit Example

- At this point in the failure process, progression has continued and intervention was unsuccessful.
- Erosion tunnel will enlarge and lead to breach unless the reservoir water surface drops.

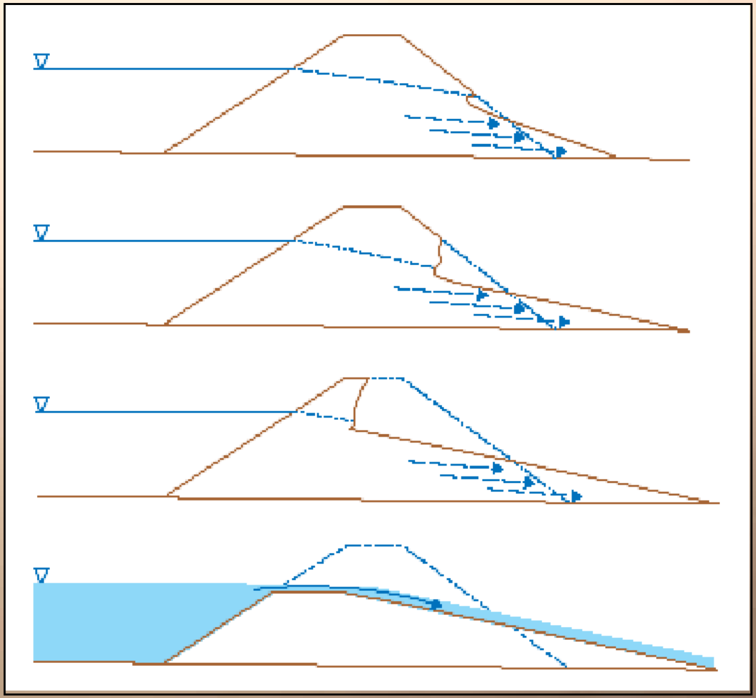
Breach by Unraveling

- Downstream rockfill zone begins to be eroded by high seepage flows exiting the downstream slope (usually at the toe), causing slope instability and a series of slope failures that ultimately lead to a failure that takes out the crest.
- Solvik (1995) proposed a method to assess the stable boulder size to prevent unraveling.



Breach by Sloughing

- Some cohesionless embankments have failed by a similar sloughing process ("progressive erosion" or "saturation failure")
- Particles removed similar to BEP, but roof is not stable, and material collapses into the void, temporarily stopping pipe development.
  - Mechanism repeats until downstream slope failure occurs or the core is breached.



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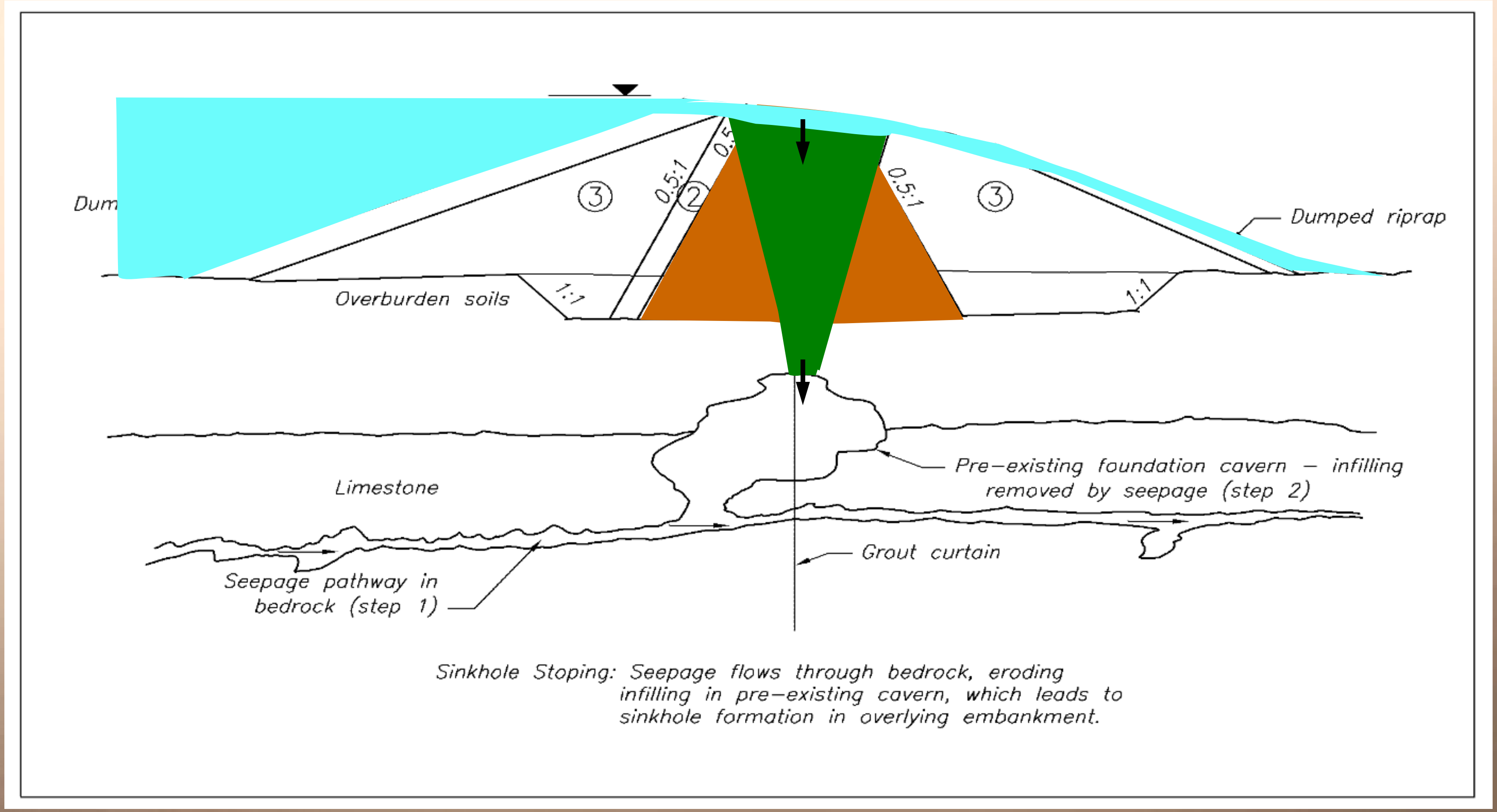
Breach by Sinkhole Development



Breach by Sinkhole Development

- Sinkhole must be sufficiently large to drop the crest below the reservoir level or leave a small remnant not capable of holding back the reservoir.
  - Most sinkholes are small and shallow
  - Located on crest about half the time

Pablo Dam Sinkhole

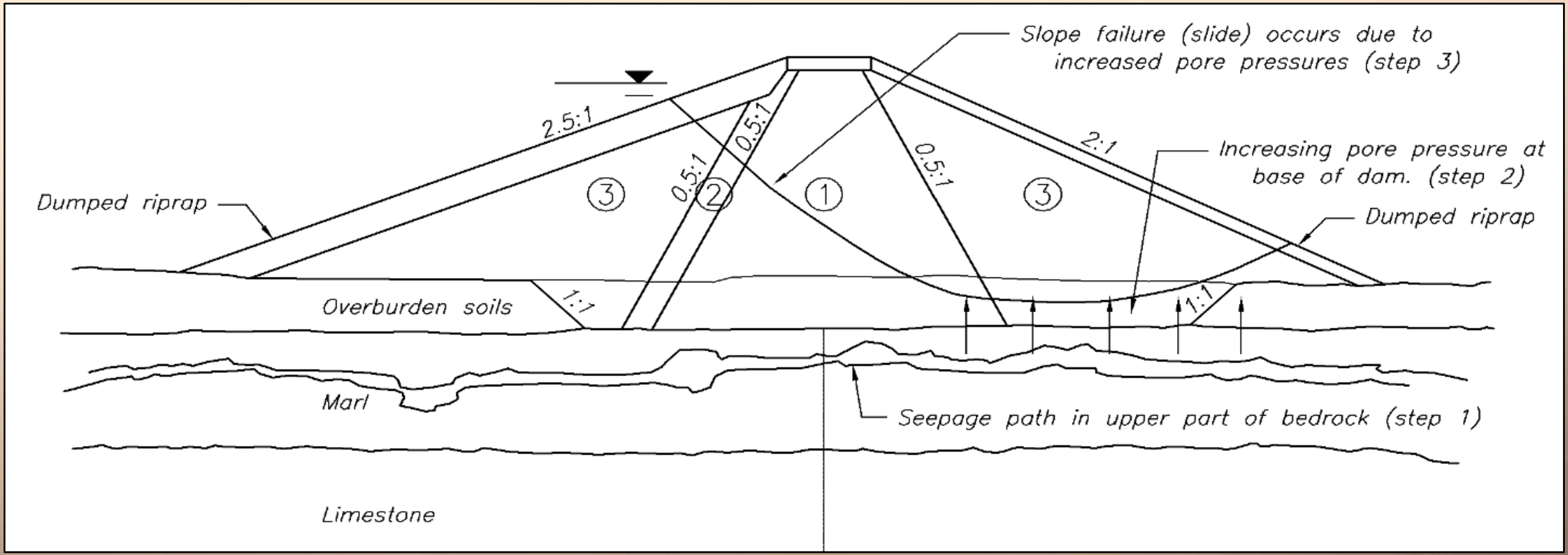
Breach by Sinkhole Development

- Sinkhole development can be a slow process, taking years to appear on the embankment surface.
- Potentially a rapid process in the final stage when it breaks through to the ground surface.
- Sinkholes could cause higher pressures within the embankment that could initiate other potential failure modes.

Breach by Slope Instability

- Internal erosion causes high pore pressures in the foundation or embankment, resulting in reduced shear strength and slope failure.
- Failure surface either intersects the reservoir or the slope deformations are significant enough that the remnant can't resist the reservoir load.
- Generally not considered to be a very likely breach mechanism for most well constructed dams.

Illustration of Internal Erosion Leading to Slope Instability



Breach by Slope Instability

- Factors to consider:
  - Freeboard relative to the embankment height
  - Crest width
  - Do drainage measures exist to prevent high pore pressures (e.g., filter/drain, relief wells)?
  - Will the slip surface impact the crest enough to lose freeboard?
  - Parametric stability analyses
    - Evaluate the effect of increased pore pressures on factor of safety
    - Evaluate possible geometry of failure surface